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Characterization of Contaminated Nuclear Sites, Facilities and Materials: Accelerators

Evaluation Research Corp.
Oak Ridge, TN

Prepared for

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CHARACTERIZATION OF CONTAMINATED NUCLEAR SITES, FACILITIES AND MATERIALS

(Accelerators)

February 1983

Prepared for:

U.S. Environmental Protection Agency
Washington, D.C.

Prepared by:

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The Environmental Protection Agency (EPA) is developing environmental protection standards for evaluating the risks and characterizing problems associated with disposal of radioactive wastes arising from decontamination and decommissioning (D&D) operations. A list was compiled of organizations operating 1042 active particle accelerators. A review of the operational health physics problems at these facilities, was used to characterize the types and volumes of wastes which are likely to result from D&D. the accelerators were grouped into three general classes (constant direct current field machines, incremental acceleration machines and magnetic field machines) based upon the method of particle acceleration.

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TABLE OF CONTENTS

Section Page

ABSTRACT viii

1.0 INTRODUCTION 1

  1.1 EPA Program and Objectives 1
  1.2 Scope of the Present Project 2

2.0 METHODOLOGY 3

  2.1 Approach 3
  2.2 Literature Review 3
  2.3 Other Information Sources 6
    2.3.1 Contacts with State and Territorial Governments 6
    2.3.2 Other Contacts 8
  2.4 Assumptions for Decontamination and Decommissioning 8
    2.4.1 Criteria for Decommissioning 8
    2.4.2 Waste Volumes 11
  2.5 Categorization of Facilities 12

3.0 DESCRIPTION OF FACILITIES 13

  3.1 Facility Characterization 13
    3.1.1 Location of Particle Accelerators 13
    3.1.2 Use of Particle Accelerators 15
    3.1.3 Operating Lifetime 22
  3.2 Waste Characterization 22
    3.2.1 Radiological Characteristics 22
    3.2.2 Physical Characteristics 33
    3.2.3 Chemical Characteristics 35
    3.2.4 Handling Considerations 35

4.0 GENERIC FACILITY DESCRIPTION 37

  4.1 Operating Lifetime 37
  4.2 Waste Characterization 38
  4.3 Decontamination and Decommissioning Alternatives 39
  4.4 Recyclable Components 42

5.0 FACILITY AND SITE-SPECIFIC ISSUES 44

  5.1 On-Site Disposal 44
  5.2 Long-Lived Induced Activity 44
  5.3 Dismantling Procedures 44
  5.4 Assembly Procedures 45

6.0 SUMMARY AND CONCLUSION 45

REFERENCES 58

TABLE OF CONTENTS (Ctd.)

Page

APPENDIX A. LIST OF ACCELERATOR FACILITIES 61

APPENDIX B. PERTINENT LITERATURE 130

LIST OF FIGURES

Figure PAGE

2.1 Sample Form Letter Sent to States 7

3.1 Accelerator Use by Machine Type Based upon BRH 1977 Questionnaire 19

LIST OF TABLES

Table | Page

3.1 Distribution of Particle Accelerators by State 14

3.2 Particle Accelerator Distribution by NRC Region 16

3.3 States with the Largest Number of Active Units in Each Particle Accelerator Class 17

3.4 Summary of Radionuclides Commonly Identified in Construction Materials Irradiated Around Accelerators 24

3.5 Potential Areas of Induced Radioactivity Based Upon Particles Accelerated and Energy 26

3.6 Maximum Activities Remaining in Orsay 155 MeV Synchrocyclotron Components after 2 Months of Storage . . . 29

3.7 Estimated Wastes Associated with the Dismantling of the ZGS 31

3.8 Survey of Radioactivity in the Cambridge Electron Accelerator Synchrotron as of June 2, 1973 32

4.1 Possible Sequences of Accelerator Decommissioning 43

6.1 Summary of Accelerator Facilities 46

6.2 Estimates of Mass and Volume of Radioactive Waste from Accelerator Facilities 48

6.3 Potential Radioactive Waste Produced from D&D of Betatron Facilities 49

6.4 Potential Radioactive Waste Produced from D&D of Synchrocyclotron Facilities 50

6.5 Potential Radioactive Waste Produced from D&D of Cyclotron Facilities 51

6.6 Potential Radioactive Waste Produced from D&D of Linear Accelerator Facilities 52

6.7 Potential Radioactive Waste Produced from D&D of Synchrotron Facilities 53

LIST OF TABLES (Ctd.)

Table Page

6.8 Potential Radioactive Wastes Produced from D&D of Direct Current Machines 54

6.9 Potential Radioactive Wastes Produced from D&D of All Accelerator Facilities 55

6.10 Potential Radioactive Wastes Produced from D&D of All Accelerator Facilities from 1940-2000 56

ABSTRACT

The Environmental Protection Agency (EPA) is developing environmental protection standards for evaluating the risks and characterizing problems associated with disposal of radioactive wastes arising from decontamination and decommissioning (D&D) operations. A list was compiled of organizations operating 1042 active particle accelerators. A review of the operational health physics problems at these facilities, as well as at previously decommissioned facilities, was used to characterize the types and volumes of wastes which are likely to result from D&D. The accelerators were grouped into three general classes (constant direct current field machines, incremental acceleration machines and magnetic field machines) based upon the method of particle acceleration:

- Incremental Acceleration Machines
  Sixty-nine percent (719) of the 1042 units listed are incremental acceleration machines. Induced activity levels are generally high in these machines and remote handling may be required for target probes, beam extraction components, and other highly activated components. The projected mass of radioactive waste from the D&D of accelerators in this class between the years 1981 and 2000 ranges from 74000-620000 tons.

- Constant Direct Current Machines
  Twenty-six percent (273) of the 1042 units listed are Cockroft-Walton and Van de Graaff accelerators. Low levels of induced activity are generally located in the beam line components and the acceleration beam itself. The projected mass of waste resulting from D&D of facilities in this class is about 20 tons.

- Magnetic Field Machines
  Five percent (50) of the 1042 accelerators identified in our survey were betatrons. The

projected mass of radioactive waste from the D&D of betatrons between the years 1981 and 2000 ranges from 900-3000 tons.

The residual radioactivity at these facilities is the induced activity in structural components of the accelerator and its housing. The long-lived radionuclides are ^{60}Co (5.3 years), ^{55}Fe (2.7 years), and ^{22}Na (2.6 years). Many of the short half-life radionuclides induced in the components will decay away in a few years. The projected volumes of radioactive wastes generated as a result of D&D of all active accelerator facilities, assuming no component recycling and no "decay-delay" action in D&D, are 10,000-200,000 m^3 for the period 1981-1990 and 20,000-300,000 m^3 for the period 1991-2000. Thus, a significant volume of radioactive waste will be generated by the D&D of accelerator facilities through the year 2000.

1.0 INTRODUCTION

Since the initiation of the Manhattan Project in the early 1940's, several thousand sites throughout the United States have conducted activities using naturally radioactive materials, man-made radioactive materials and/or radiation producing devices. Several hundred of these sites, or facilities at some of the sites, are no longer used and have been closed. Some have been decontaminated and decommissioned, or are awaiting decommissioning. Eventually, all such sites will need to be decommissioned. The subject of nuclear facility decommissioning has been of increasing concern over the past several years and has been addressed by the Comptroller General in a 1977 report to the Congress. (USGAO77) The primary thrust of the GAO report concerns the nuclear power industry; however, other aspects, including particle accelerators, were recognized as potential problems. (Op79a) Guidelines are needed to establish procedures for future decontamination and decommissioning of all nuclear facilities, including accelerator facilities.

1.1 EPA Program and Objectives

The Nuclear Regulatory Commission (NRC), Department of Energy (DOE), and the Environmental Protection Agency (EPA) are all involved in the preparation of procedures and guidelines for decontamination and decommissioning which will assure that nuclear facilities are retired in a manner acceptable to the various regulatory agencies and the general public, and which can be achieved by the nuclear industry. The operation of private accelerators is generally regulated by authorities of the State in which the facility is located. However, operation of accelerators and units owned by the federal government or located on federal property is controlled by the federal government. In the future, plans for decontamination and decommissioning procedures to be followed at the time of shutdown may be required prior to start of operations at an accelerator facility. Following decontamination and decommissioning, the EPA assumes responsibility for protecting public health.

The EPA is developing a series of enviromental protection standards for disposal of radioactive waste not covered by the Atomic Energy Act based upon provisions of the Resource Conservation and Recovery Act of 1976. Development of these standards involves estimating the volume and characteristics of the radioactive wastes that will be generated by decommissioning activities. Radiation protection guidance is needed in the form of acceptable residual radioactivity levels for use in planning and implementing decontamination and decommissioning of all nuclear facilities. The permitted residual levels of radioactivity will influence the amount of material that will need to be removed. Technical assessments are required to characterize the problems, evaluate the risks, examine different decontamination and decommissioning options available, and any occupational risk associated with each method to support development of such guidance.

1.2 Scope of the Present Project

An estimated 1200 accelerators have been operated in the United States. They range from small Van de Graaff generators to multi-GeV research synchrotrons. (Mu78) Eighty-one accelerators have been decommissioned since the 1930's. (Op79c) In this study we have identified 1042 active accelerator units and 107 inactive or decommissioned units. However, information on the problems encountered and radioactive waste resulting from these operations is limited. The purpose of this work is to characterize the radiological problems associated with the decontamination and decommissioning of different types of accelerator facilities, and to estimate the volume of radioactive wastes generated by decontamination and decommissioning activities.

Information was compiled on the types, locations, and radiological problems encountered in decontamination and decommissioning of accelerator facilities. A list has been compiled of the operational accelerator facilities in the United States, along with those units previously decomissioned. Induced radioactivity levels, waste volumes produced from D&D operations, and potential problems in decontamination and decommissioning operations at the sites are addressed.

The decontamination and decommissioning of accelerator facilities has been discussed in great detail by several investigators. In particular, a recent report by Opelka, et al. (Op79c) proved extremely useful in this study, serving as a primary reference source for the characterization of various types of accelerator facilities and potential problems in decontamination and decommissioning activities. The primary emphasis of the current project has been the compilation of a relatively comprehensive list of accelerator facilities in the United States, and the estimation of volumes of radioactive waste produced from decontamination and decommissioning.

2.0 METHODOLOGY

2.1 Approach

Listings of particle accelerators in the United States have been compiled by various authors. However, these lists are generally specific to one type of accelerator or one energy range. In some cases, lists were compiled according to the primary use of the accelerator.

In compiling a comprehensive list of facilities for this study, information was obtained on all types of accelerators from the low energy Van de Graaff generators to the high energy proton synchrotrons. A number of information sources were used to compile the listing of accelerator facilities in Appendix A. These include:

1) Library and data base searches at Oak Ridge National Laboratory (ORNL) and at DOE's Technical Information Center (TIC) for information on specific accelerators and on different classes of accelerators.

2) Contact with Federal, state and territorial agencies to obtain available accelerator registration lists and specific information concerning decommissioned units.

3) Contacts with individuals known to be involved in compiling information on accelerators or conducting studies on accelerator decontamination and decommissioning.

2.2 Literature Review

A literature search was conducted for information concerning different classes of particle accelerators. Library and data base searches at the

Central Research Library (CRL) and the Information Center Complex (ICC) of Oak Ridge National Laboratory (ORNL) and the DOE Technical Information Center (TIC) in Oak Ridge were used to locate pertinent documents. In addition, personal contacts were made with staff at ORNL involved in accelerator work and with NRC staff members to locate additional information sources.

The following keywords were used in an initial search of the data bases:

- Accelerators (including cyclotrons, synchrotrons, and synchrocyclotrons),
- Decommissioning,
- Reactor Decommissioning,
- Demolition, and
- Dismantling.

A total of seventeen publications were identified using the keywords listed above. Of the seventeen, four lists of accelerator facilities were located using the keyword 'accelerators.' (Ho67, Ho69, Ho74, Ma78) These were primarily lists of accelerators classified according to energy of the emitted particles (i.e., high energy) and specific classes of accelerators (i.e., tandem accelerators). These lists were incorporated into the final listing of particle accelerators presented in Appendix A.

The first four accelerator information sources identified were compiled by F.T. Howard of the Accelerator Information Center (AIC) and John Martin, both of Oak Ridge National Laboratory. (Ho67, Ho69, Ho74 and Ma78) The data in these publications had been obtained by sending questionnaires to all known operating accelerator facilities. Information was collected on a number of items, ranging from the energy of the particles accelerated to the size of the research staff.

The DOE Technical Information Center (TIC) in Oak Ridge accessed the Energy Data Base and Nuclear Science Abstracts Data Base using the keyword "Decontamination and Decommissioning." One of the documents identified by this search was by Gerald A. Behman of the University of California Radiation Laboratory in Berkeley, CA, and described active accelerator facilities in 1958. (Be58) Information on each accelerator included the following: location, owner/operator, type, dimensions, particles accelerated, and the particle energy in MeV.

The Information Center Complex (ICC) at ORNL has access to several energy and nuclear related information data bases. An ICC data base search was conducted for information pertinent to decontamination and decommissioning of accelerator facilities. The data bases searched, keywords used, and number of records identified were:

- Decontamination & Decommissioning Data Base
  - Laboratory Studies and Volume Forecasts (5 records)
  - Modeling and Codes (34 records)
  - Field Studies, Forecasting, Volume, Environmental Impacts and Radionuclides (89 records)

- Integrated Waste Data Base
  - Remedial Action Fields (159 records)

Of the 287 records located, only seven were found to pertain directly to the work effort. These references dealt primarily with the decontamination and decommissioning of research facilities.

A review of publications by three researchers, J. H. Opelka, R. L. Mundis, and J. M. Peterson, at Argonne National Laboratory (ANL) provided excellent additional sources of information on accelerator decontamination and decommissioning. (Op79a, Op79b, Op79c, Pet79, Mu78) These documents were used as primary sources of detailed information on waste characterization at accelerator facilities. The report by Opelka, et al. (Op79c) gives a very comprehensive description of various accelerator facilities and the problems associated with potential decontamination and decommissioning activities.

This literature review primarily identified larger energy research accelerators in use. These listings were cross-checked and a listing for each type of particle accelerator was compiled. It was necessary to contact the individual states to obtain information on new facilities and smaller accelerator units.

2.3 Other Information Sources

2.3.1 Contacts with State and Territorial Governments

The listings of the larger research accelerators generally overlooked many units used for research at universities, medical therapy units and small industrial accelerators. To make the accelerator listing as complete as possible, letters were sent to the radiological control offices of each of the 50 states, Puerto Rico and the District of Columbia to gather information on registered accelerator units. Figure 2.1 is a typical form letter sent to the states. Those states which did not respond to the initial inquiry were sent additional follow-up letters; telephone inquiries were made to states which failed to respond to the second letters. ERC requested reference material or sources of information from each state or territory pertaining to the items listed below:

- Accelerator facilities
- Radiopharmaceutical manufacturers and suppliers
- Radioisotope manufacturers and suppliers
- Independent research and development institutions

Only accelerators are discussed in this report; radiopharmaceutical manufacturers and suppliers, radioisotope manufacturers and suppliers and independent research and development institutions are discussed elsewhere. (ERC82a, ERC82b) Forty-six states and Puerto Rico responded to our request for information. Five states (Alabama, Colorado, Maryland, Massachusetts, and North Carolina) were unable to supply the requested information due to legislative constraints or personnel limitations. In some instances, the states offered to allow us to review their records and extract the necessary information; however, time and budget precluded these site visits and reviews. No information was received from five states (Oklahoma, Connecticut, Virginia, New Jersey and the District of Columbia) even though we made numerous requests.

The information requested from the individual states for each accelerator facility included:

August 18, 1981

<gender> <first> <last>
<where>

Dear <gender> <last>:

Evaluation Research Corporation has a contract with the Environmental Protection Agency to characterize problems that may be encountered in the decontamination and decommissioning of facilities which are or were formerly licensed by the U.S. Nuclear Regulatory Commission or Agreement States, and with registered accelerator facilities. Our interests are restricted to those used to manufacture radiopharmaceuticals and radioisotopes and independent research and development institutions.

If you have a listing of facilities used for the manufacture of radiopharmaceuticals and radioisotopes and of independent research institutions in your State we would appreciate receiving a copy of the list. We are also compiling information on the likely radiological conditions of the sites and facilities. Any sources of information you have or are aware of concerning the types of operations and/or types and quantities of radionuclides authorized for possession, would be very helpful.

The U.S. Bureau of Radiological Health, "Report of State and Local Radiological Health Programs" Fiscal Year 1977, (HEW Pub. No. 78-8034) lists the number of accelerators registered by your state but no information is given as to type or location. Our data base and library searches have provided specific identification for relatively few of the accelerators listed for your State. Again, if information or references are available we would like to receive a copy of the publication or the publication name and number.

If you have any questions with respect to this enquiry please contact me or Ms. Joann Epler (Ph. 615-482-7973). Thank you for your consideration.

Sincerely,

Donald Jacobs
Manager, Oak Ridge Operations

DGJ:mgr

Figure 2.1 Sample Form Letter Sent to States

- Name and address of facility
- Unit(s) at the facility address
- Date of first beam (if known)
- Shut down date (if applicable)

In some instances, additional contacts were necessary to supplement information from the initial requests.

The list of accelerator facilities and pertinent, available information is tabulated in Appendix A. Although accelerators are generally regulated by individual states, the quality of information available from state authorities varies widely. Some states have a detailed registration list of accelerators in their state, while other states register the units only by obtaining the number of units and their energies at a particular facility. Variations in the definition of a particle accelerator used by different states required the addition of some "irregular" particle accelerator listings.

2.3.2 Other contacts

The "Patterns of Care Study" conducted in the late 1970's by the American College of Radiology's (ACR) Philadelphia office identifies 751 medical therapy units with peak energies of less than 20 MeV identified as being in use in hospitals, medical centers and physicians' offices in the United States. (Gr81) Quite often smaller medical therapy units are excluded from lists of linear accelerators, since there is no induced radioactivity in components. The ACR list would have been helpful for verification of state contacts. Unfortunately the list is considered confidential and could not be made available for our use. A summary tabulation of medical therapy units categorized by maximum particle energies was supplied by Dr. Graham Grundy of ACR, and proved helpful in the estimation of waste volumes from these facilities.

2.4 Assumptions for Decontamination and Decommissioning

2.4.1 Criteria for decommissioning

The basic precept of radiation protection standards is that all radiation is potentially harmful and that radiation exposure from all sources of man-made exposure should be maintained "as low as reasonably achievable" (ALARA). However, in our technological society all persons are exposed to radiation from natural background, medical and dental X-rays, consumer products, weapons fallout, and other sources of natural and man-made radiation.

The ICRP has established a radiation dose limit of 0.5 rem (500 mrem) per year in consideration of somatic effects in the general population. (ICRP77) Early ICRP recommendations suggested a genetic dose limit of 5 rem per 30 years (0.2 rem per year) for members of the general public. (ICRP59) In more recent recommendations, the ICRP suggested that continued use of this limit might be construed to imply acceptability of population exposures that are significantly greater than those considered either necessary or probable. (ICRP77) In any case, all exposure limits should be considered upper bounds, and actual exposures should be maintained as low as reasonably achievable.

Operation of accelerator facilities is generally regulated by the state in which the facility is located. When the unit is shut down, no federal agency oversees the decommissioning; the state regulatory agency is responsible for all aspects of decommissioning, including the criteria to be used. An exception exists for accelerators located on Federal property where the operation is controlled by the Federal government. (Op79c) The number of accelerators in operation has increased sharply over the past 20 years and decommissioning of these facilities is increasing rapidly.

One problem encountered is that several agencies are responsible for regulating accelerators. In the state of New York, for example, four agencies are responsible for regulating the use of accelerators: the New York Departments of (1) Health, (2) Labor, (3) Environmental Conservation, and (4) The New York City Department of Health. In the state of Illinois the Department of Public Health regulates all accelerators, except those at state universities which are regulated by the Department of Education. (Op79c)

A second problem is that some states have no guidelines for decommissioning accelerators. A review conducted by Opelka (Op79c) indicated that very few states have guidelines or regulations for decommissioning accelerators. Some states had guidelines for decommissioning, but not explicitly for accelerators. One state indicated it would use NRC Regulatory Guide 1.86 (USNRC74) as a guide for decommissioning; but this guide deals only with acceptable radiation levels to the general public from surface contamination on equipment and materials. No state has guidelines pertaining to acceptable induced radioactivity levels following decommissioning of an accelerator facility. Also, no standards exist for residual activity in components and structural materials which may be sold to the general public for scrap.

One instance in which criteria chosen for decommissioning were explicitly stated was at the Carnegie-Mellon University synchrocyclotron located at the Nuclear Research Center, Saxonburg, Pennsylvania. This facility was closed in January 1964, and was ultimately decommissioned in 1973. Radioactivity was actually removed rather than covered with shielding. (Op79c) The final criterion for decontamination was set at exposure levels twice natural background (2 x 0.015 mR/hr = 0.03 mR/hr). This level of exposure would deliver an annual dose of 260 mrem, about one half the annual dose limit for individual members of the general public specified by ICRP. (ICRP77)

During decommissioning of the Heavy Ion Linear Accelerator (HILAC) at Yale University, any item which had detectable radioactivity was handled as radioactive waste. (Pr76) Measurable activity was defined as 1 mCi for ^{60}Co, ^{65}Zn, and ^{22}Na in components counted using a GeLi detector at 10" for a 30 minute counting period. (Op79c)

The basic conclusions drawn from these two cases is that the criteria used during decommissioning of accelerator facilities are highly variable from site to site. The need for residual radioactivity guidelines for future decommissionings is evident. For this project, all materials with radiation levels above background will be treated as radioactive wastes.

2.4.2 Waste Volumes

Several basic assumptions are required for estimating waste volumes generated during the decontamination and decommissioning of accelerator facilities. The assumptions are considered to be conservative enough to allow some leeway for variation yet not conservative as to unrealistically represent the problem.

It is difficult to document or verify waste volumes generated from decontamination and decommissioning operations. Average values of the waste volume per accelerator unit of a given category and size were estimated from a limited (and not necessarily statistically representative) sampling of accelerator units. (Op79a, Op79b, Op79c, Mu78) We found no references with projected or actual volumes of waste that would result from the decommissioning of some types of accelerators. The following assumptions were made to correct this problem: tandem accelerators were evaluated as electrostatic accelerators, betatrons were classified and evaluated as cyclotrons, and miscellaneous and neutron generator facilities were classified as linear accelerators. Estimated waste volumes in some instances included the accelerator plus a 10% allowance for auxiliary components and other miscellaneous materials. (Op79c) In those cases where the actual energy of a particular accelerator was unavailable, the unit was assumed to be of the average size of other units in that class of accelerators.

The majority of waste materials within the accelerator and ancillary equipment are comprised of iron and copper. In some cases significant amounts of these materials may be recoverable. However, as a conservative measure in this analysis, all contaminated materials are treated as radioactive waste and no recycling is considered. It is anticipated, though, that in most cases some components will be recycled for use at the same site or transferred to another site.

Knowledgeable members of the health physics profession have indicated that those accelerators with peak particle energies of less than 10 MeV have little induced radioactivity. (Op79a, Op79b) Therefore, we assume in our waste volume estimates that those linear accelerator units less than 10 MeV will produce a volume of waste so small that it is negligible for our estimates.

2.5 Categorization of Facilities

The accelerator lists presented in Appendix A were categorized according to the method used to achieve the desired particle velocity. The three general classes of particle accelerators are: (Ce79)

- Constant Direct Current Field Machines (e.g. Cockroft-Walton, Van de Graaff, insulated core transformer, and Dynamitron),
- Incremental Acceleration Machines (e.g. Linear accelerators, cyclotrons, and their derivatives), and
- Magnetic Field Machines (e.g. Betatrons).

The lists were then further subdivided within the three main classes into the following groups:

Constant Direct Current Machines
- Direct Current Machines
  - Van de Graaff Generators
  - Cockroft-Walton Machines
  - Dynamitrons
- Tandem Accelerators

Incremental Accelerators
- Linear Accelerators
- Cyclotrons
- Synchrotrons
- Synchrocyclotrons

Magnetic Field Machines
- Betatrons

In some instances, two or more types of accelerators are located at one facility. Where this has happened, the facilities have been listed under their respective individual categories.

Neutron generators, ion implanters and cohesive binders are registered and/or licensed in terms of their function rather than according to the accelerating principle employed. These units are usually of low energy and are listed here only to provide as complete a list as possible. In addition, storage rings have been included for the sake of completeness even though only two entries were recorded on this list.

Energy levels are used by some states (e.g. California) as the primary classification criteria for accelerators, and this causes some additional inconsistencies with regard to the lists. Other states (e.g. Texas) register the accelerator units based upon only one fact---the company sending notice of an accelerator being on site. The state radiological offices in Texas and California were unable to provide detailed information on accelerator users in these states; therefore, these users were lumped into one "miscellaneous" category. The units in this category probably would fit into one of the other classes of accelerators on our list. However, due to a lack of sufficient information, this resolution was not possible, and these miscellaneous accelerators have been classified as linear accelerators for this analysis.

3.0 DESCRIPTION OF FACILITIES

3.1 Facility Characterization

3.1.1 Location of Particle Acclerators by State

Estimates of the number of particle accelerators located in the individual states are presented in an annual report by the Bureau of Radiological Health (BRH). (USBRH77) In some cases, states were unable to respond to the BRH questionnaire used to gather this information; this missing and incomplete information results in an additional degree of inaccuracy.

As a means to supplement and verify the BRH estimates, ERC compiled the listing of particle accelerators presented in Appendix A using the methods discussed in Section 2. Federal facilities were included when the information was supplied by state offices or other information sources, but in some cases this information was not available and no special effort was made to obtain information on Federal accelerator units. The state-by-state breakdown of particle accelerator locations is shown in Table 3.1.

Table 3.1

Distribution[c] of Particle Accelerators by State[a]

State / Accelerator Category	Betatrons	Cyclotrons	D.C. Machines	Linear Accelerators	Neutron Generators	Synchrotrons	Synchro-cyclotrons	Tandem Accelerators	Unclassified[f]	Total[b]
Alabama[d]			5	1						6
Alaska[e]				1						1
Arizona[e]			1	20						21
Arkansas[e]			3 (1)	4					1	8 (1)
California[e]	1	12 (4)	19	23 (3)		3 (2)	1 (1)	2 (1)	142	203 (11)
Colorado[d]		1								1
Connecticut[d]		2	2	2				1		7
Delaware[e]			4	1						5
D.C.[d]	1 (1)	5 (1)	10 (1)	1		1			1	19 (3)
Florida[e]	2	1	10 (1)	60				1		74 (1)
Georgia[e]	2		5	15					1	23
Hawaii[e]				3						3
Idaho[e]			1	3						4
Illinois[d]	2 (4)	4 (2)	10 (1)	7	1	4 (1)	0 (1)	2		30 (9)
Indiana[e]	1	2 (2)	2	2		0 (1)		2	5	14 (3)
Iowa[e]			4 (1)	11		1 (2)				16 (3)
Kansas[d]			1 (1)	1	1 (1)			1 (1)		4 (3)
Kentucky[e]			5	6	1					12
Louisiana[e]			1 (2)	20 (2)						21 (4)
Maine[e]				4						4
Maryland[d]	1	1	6 (2)					0 (1)		8 (3)
Massachusetts[d]		6 (1)	12 (3)	2 (2)		0 (1)		1		21 (7)
Michigan[d]	2 (1)	1 (3)	6	6		0 (1)		1		16 (5)
Minnesota[e]			0 (1)	18 (1)				1		19 (2)
Mississippi[e]				4						4
Missouri[e]	2	7		11						20
Montana[e]			1	5						6
Nebraska[e]			1	8						9
Nevada[d]			2							2
New Hampshire[e]			0 (1)	3						3 (1)
New Jersey[d]	1	2	7	2		0 (1)	0 (1)	2		14 (2)
New Mexico[e]	0 (13)	0 (1)	6 (2)	5 (1)				1		12 (17)
New York[d]	4 (3)	4 (4)	13 (1)	5 (1)		4 (3)	1 (1)	3		34 (13)
North Carolina[d]		2	1					1		4
North Dakota[e]				3						3
Ohio[e]	6	1 (1)	6 (1)	4	1			1	28	47 (2)

The state reporting the largest number of particle accelerators was California with 202 active units (21% of the active total). The second largest number of units was reported in Florida with 74 active units (8% of the total). The States reporting the largest number of decommissioned units were New Mexico with 17, followed by New York with 13 and California with 11.

A summary of particle accelerators in each NRC region is presented in Table 3.2. As expected, highly industralized states (or regions) and highly populated areas have the greatest concentration of accelerator units. In some cases, a region is dominated by one or more states with a particularly large concentration of accelerators; for example, California contributes the majority of accelerator units in Region 5, and Florida dominates Region 2. Overall, however, it is interesting to note the relatively uniform distribution of accelerators among the NRC regions.

The state with the largest number of active accelerator units in each machine category is listed in Table 3.3 These results also point to the same conclusion that the more populous, industrialized states have a larger number of accelerators in their states. Florida dominates the linear accelerator category due to its large number of medical accelerator facilities.

3.1.2 Use of particle accelerators

The first particle accelerator developed was the Van de Graaff electrostatic generator in the late 1920's. (Va31) In the early days of accelerator operations, the accelerator was used primarily for research. The linear accelerator was developed in the late 1940's by Alvarez (Al46) and is currently the most widely used accelerator. As noted by Burrill (Bu69), accelerators now have broad application in physics, chemistry, radiobiology, radiation therapy, radiation processing and sterilization, industrial radiography and activation analysis. Units accelerating particles above 100 MeV still are devoted primarily to fundamental research. (Bu69)

Table 3.2

Particle Accelerator Distribution by NRC Region*

NRC Region	Active Units	Inactive or Decommissioned Units
1 (ME, VT, NH, MA, CT, RI, NY, PA NJ, DE, MD, DC)	164	33
2 (VA, WV, KY, NC, TN, SC, GA, FL, AL, MS, PR, VI)	188	8
3 (OH, IN, MI, WI, MN, IL, MO, IA)	195	24
4 (AR, LA, TX, OK, KS, NE, SD, ND, MT, WY, UT, NM, CO, ID)	164	31
5 (WA, OR, CA, NV, AZ, AK, HI)	289	13

*The total number of particle accelerators in this table does not equal the total number of units listed in Appendix A because ion implanters, cohesive binders, and storage rings are not included here.

Table 3.3

States with the Largest Number of Active Units in Each Particle Accelerator Class

Class of Particle Accelerator	State(s)	Number of Active Units in State
Linear Accelerators	Florida	60
Direct Current Machines	California	19
Cyclotrons	California	12
Neutron Generators	Pennsylvania	8
Betatrons	Wisconsin	7
Synchrotrons	New York, Illinois	4
Tandem Accelerators	New York	3
Synchrocyclotrons	California, New York	1

The BRH report discussed in section 3.1.1 does not categorize accelerator use by type of machine. (USBRH77) The questionnaire response data was not included in the BRH report, but a 1979 report by Cehn (Ce79) compiled the 1977 use data into the seven accelerator categories shown in Figure 3.1. From this figure it is clear that linacs are the most widely used accelerator. Our census results verified this conclusion; 42% of the particle accelerators identified in this study were linear accelerators.

By custom, a linear accelerator is a high frequency accelerator with a straight particle trajectory. (Ka64) These units are replacing older medical therapy accelerators and teletherapy sources that require periodic replacement due to radioactive decay. (USBRH75) An estimated 590 linear accelerators were operating in 1977 and about 70% of these were used in medical therapy applications. (Ce79) In the late 1970's, the use of small linear accelerators for medical therapy was increasing by 200 to 250 units per year, with an eventual projected total of 2000 units in the United States. (Mu78) However, the "Patterns of Care Study" conducted by the American College of Radiology (ACR) indicated 751 units currently used in medical therapy with 10% of the data yet to be recorded. (Gr81)

The remainder of the linear accelerators are used at universities for research applications, in industrial settings for production purposes, and, in some cases, as injectors for larger accelerator units. Quite often proton linear accelerators are used as injectors for larger units. (Pa73) The most popular application of industrial accelerators is ion implantation. (Co76) Other applications include industrial radiography, analysis of materials, food processing and sterilization, and curing of coatings and paint. (Ce79)

Sixty cyclotron facilities were identified in our census of active particle accelerators. This represents 6% of the 1042 active accelerator units. Twenty-two inactive units were identified, amounting to 21% of the total 107 decommissioned units. In the cyclotron, a particle moves across an unwinding spiral plane crossing the same accelerating gap many times. Due to relativistic increases in mass, a stable orbit above approximately 25 MeV cannot be achieved. (Ka64) Universities and national

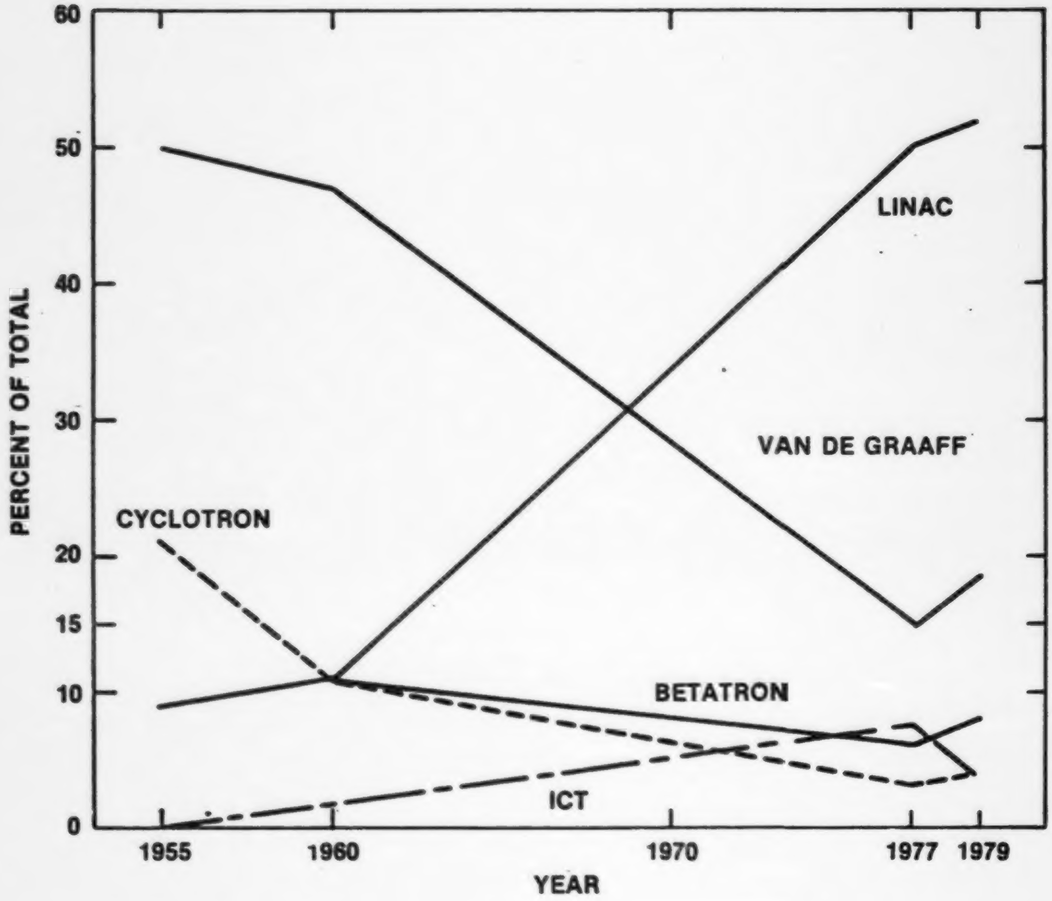

Figure 3.1 Accelerator Use by Machine Type Based Upon BRH 1977 Questionnaire (Ce79)

laboratories are the primary users of cyclotrons for research purposes. Hospitals and independent corporations use them primarily for medical therapy and radioisotope production.

Direct current machines (Van de Graaff operators and Cockroft-Walton machines) operate by applying a constant direct current electrical field through which the charged particles pass. (Ce79) These machines, especially Van de Graaffs, have wide application in medical centers for diagnostic and therapeutic purposes. These units are also used for research and industrial applications as described by Burrill. (Bu69) The Dynamitron, a modernized version of the Cockroft-Walton, is used primarily in radiation research and processing. (Pa73)

The census identified 157 Van de Graaff units (16% of the total active units) used by a variety of organizations including universities, hospitals, and industries. At some facilities Van de Graaffs and Cockroft-Walton units are used as injectors for large accelerators. It is anticipated that units in this class currently used for medical therapy purposes eventually will be replaced by linear accelerators. (USBRH75) Thirty-four (4% of the total active units) Cockroft-Walton and Dynamitron units were identified in the census; applications for these models are essentially the same as those described for Van de Graaff units.

Tandem accelerators consist of two or, in a few instances, three accelerators, generally Van de Graaffs, used in series such that the particles are energized twice instead of the single acceleration in a typical Van de Graaff. These units are used primarily in universities for research applications. Our census identified 27 active units (3% of the total active accelerators) and 5 decommissioned units (5% of the total inactive units).

Betatrons were developed in the 1920's and 1930's and are still in operation. (Pa73) The first operating unit was built in 1941 by Kerst and used for the acceleration of electrons in circular orbits. (Ke41) Betatrons have wide applications in radiation therapy, nondestructive testing and research. (Pa73) Fifty active units (5% of the total active units) were identified in our census and 22 former units (21% of the inactive units) have been decommissioned. The primary operating locations are in hospitals and industrial facilities. In addition, some users were identified at universities and national laboratories.

Synchrocyclotrons overcome the relativistic mass problems encountered with cyclotrons by changing simultaneously the frequency of the accelerating field and the magnitude of the magnetic induction. (Ka64) Eight synchrocyclotrons were identified in our census with only 2 units remaining active. These accelerators are used for generating particles, generally within the range of 200-800 MeV, and are used primarily for research. (Bu69)

The synchrotron was developed in the 1940's and was derived from the cyclotron and the betatrons. (Pa73) Seventeen active synchrotrons and 13 decommissioned units were identified from the ERC census. These units are used almost exclusively by universities and national laboratories for research purposes.

The following three classes of machines are classified as accelerators based upon their function, not the method used to accelerate the particles. Neutron Generators are used primarily by the industrial community and universities for the production of neutrons. The main industrial use is radiography, while the principal academic application is research. (Ce79) Cohesive Binders are classed as particle accelerators in the state of South Carolina; these units are used for irradiating fabric and cable to increase its resistance to tearing. (Sh81) Ion Implanters are used by the semiconductor industry to implant ions in silicon and germanium. (Ce79) Many of these units are either unregistered or greatly underreported by many states. Industry sources estimate that upwards of 400 Cockroft-Walton type machines are in use as ion implanters. (Ce79)

As previously mentioned, Figure 3.1 shows the results of a census conducted by Teknekron Research in 1979 which shows the drastic decrease in the use of Van de Graaff electrostatic generators and a somewhat less pronounced decline in the use of cyclotrons. (Ce79) Conversely the percent of the total comprised by linear accelerators has steadily increased since 1960, due largely to the aforementioned increase in medical usage.

3.1.3 Operating Lifetime

The operational lifetime of accelerators is highly variable. Some accelerators, such as the small Direct Current machines, operate only 5-10 years. Conversely, the larger units, which involve greater expenditures for construction and operations, may operate for long periods of time; for example, the 730 MeV Proton Synchrocyclotron at the Lawrence Berkeley Laboratory began operations in 1946 and is still operational (37 years of operation to date).

3.2 Waste Characterization

3.2.1 Radiological Characteristics

Unlike many other types of nuclear facilities, when operations at an accelerator facility are initiated there are generally no radioactive materials at the site. As the unit is operated over a period of time, repeated scattering of particle beams may induce activation products in the concrete, steel and other structural materials (including the accelerator itself). However, the only transferable forms of contamination are the radionuclides induced on the targets, where the concentrations may be up to 2×10^3 Ci/m^3. (Ro82) The Los Alamos Meson Physics Facility (LAMPF), a proton linear accelerator, is expected to have exposure levels >>1000 R/hr in the primary target areas of the facility. (Op79a)

Estimates of the amounts of material with induced radioactivity, which is likely to make up radioactive wastes have been made by personnel at several accelerator facilities and reported by Opelka. (Op79c) The range of induced radioactivity for the proton synchrotrons was from 50 to 6800-Curies; for cyclotrons and synchrocyclotrons the estimates ranged from 5 to 2×10^5 curies. These ranges are very broad and quantities vary from site to site. Factors governing the amount of induced activity include (Mu78):

- Species of particle accelerated,
- Energy of particle accelerated,
- Beam intensity or current,
- Ratio of operating time to shutdown time, and
- Prime use of the accelerator.

Estimates of the total quantities of radionuclides contained in proton accelerators and electron accelerators have been presented in reports by Gollon and Swanson, respectively. (Go76, Sw79) These estimates are highly variable since the estimate for SREL was 200,000 curies of induced radioactivity in the accelerator and components (Op79c), while the results of the wall core borings taken by Welsh indicated only about 100 mCi of induced radioactivity in the concrete shield walls of the facility. This points out the need to characterize the wastes from each facility on a site-by-site basis.

The majority of the components of an accelerator are composed of either iron or copper. Lead and depleted uranium are used for shielding and collimating and aluminum is used in some units for magnet windings. (Mu78) A summary of radionuclides with half-lives greater than 10 minutes commonly identified in construction materials irradiated around accelerators is shown in Table 3.4. (Pa73) The major radionuclides of long-term concern are: Co-60 (5.27 years), Na-22 (2.60 years) and Fe-55 (2.94 years). Isotopes identified at the Yale-HILAC facility at the time of decommissioning included Na-22, Mn-54 (13 days), Co-60, Zn-65 (245 days), and Se-75 (120 days). (Pr76)

The National Bureau of Standards Handbook 107 provides the information in Table 3.5 as an indication of the potential of induced activity at an accelerator facility, based upon the particle accelerated and the energy range. (NBS70) In this table the "target area" is considered to be anything directly in the beam; the "vicinity" is defined

TABLE 3.4

Summary of Radionuclides Commonly Identified in Construction Materials Irradiated Around Accelerators*

Target Material	Radionuclides	Half-life	
Plastics and oils	^{7}Be	54	days
	^{11}C	20	minutes
Concrete, aluminum	as above plus,		
	^{22}Na	2.6	years
	^{24}Na	15	hours
	^{32}P	14	days
	^{42}K	12	hours
	^{45}Ca	163	days
Iron, Steel & Stainless Steel	As above, plus		
	^{42}K	13	hours
	^{43}K	23	hours
	^{44}Sc	3.9	hours
	^{44m}Sc	2.4	days
	^{46}Sc	84	days
	^{47}Sc	3.4	days
	^{48}Sc	1.8	days
	^{48}V	16	days
	^{51}Cr	28	days
	^{52}Mn	5.6	days
	^{52m}Mn	21	minutes
	^{54}Mn	313	days
	^{56}Mn	2.6	hours
	^{56}Co	79	days
	^{57}Co	271	days
	^{58}Co	71	days
	^{60}Co	5.3	years
	^{55}Fe	2.7	years

Table 3.4 (continued)

Target Material	Radionuclides	Half-life
	^{59}Fe	45 days
	^{57}Ni	36 hours
	^{60}Cu	24 minutes
Copper	as above, plus	
	^{65}Ni	2.5 hours
	^{61}Cu	3.4 hours
	^{62}Cu	9.8 minutes
	^{64}Cu	13 hours
	^{63}Zn	38 minutes
	^{65}Zn	245 days

*References: Accelerator Health Physics (Pa73); and ICRU Report No. 28 (ICRU78).

Table 3.5

Potential Areas of Induced Radioactivity Based Upon Particles Accelerated and Energy*

Particle	Energy Range (MeV)	Induced Radioactivity in Target Area	Induced Radioactivity in Vicinity
electrons	<1.7	None	None
electrons	1.7-10	Limited	Very Slight
electrons	>10	Probable	Suspect
protons, He ions	<1	Limited	None
protons, He ions	1-10	Limited	Suspect
deuterons, tritons	Any	Probable	Suspect
All ions of light atomic weight	>10	Certain	Suspect

*Reference: National Bureau of Standards Handbook 107 (NBS70) as the ring, building or accelerator vault. As the energy of particles accelerated increases, the likelihood of induced radioactivity increases.

Immediately following shutdown radioactive materials from accelerators generally have only a small fraction of their material with radiation levels higher than 1 R/hr at 3 feet. The majority of the materials have exposure rates less than 2.5 mR/hr. (Pet79) Positive ion accelerators with beam energies of less than 100 MeV have an initial decay period which is rapid and lasts approximately one week post-shutdown. The decay is then controlled by Fe-59 (45 days) and Zn-65 (245 days). In accelerators with beam energies greater than 100 MeV, the slower decaying isotopes are controlled by the radionuclides Co-57, Mn-54, and Co-60. A few accelerators with aluminum windings for the main magnet coil have Na-22 as the major long-lived radionuclide. (Mu78)

Analysis of samples from the dees and magnets of the Carnegie-Mellon synchrocyclotron identified the following radionuclides in the copper dees: Mn-54, Co-56, Co-57, Co-58, and Co-60. Mn-54 was the primary induced radionuclide in the magnets. (Op79c)

Foils of aluminum, copper, iron and stainless steel were placed around a 184-inch cyclotron at Lawrence Radiation Laboratory. The foils and the respective radionuclides identified were: Al, Na-24 (15 hr half-life); Cu, Cu-64 (13 hr); Fe and stainless steel, Mn-56 (2.6 hr) and Mn-52 (6 hr). (Bo61)

Core borings can be collected and analyzed to assess the radionuclide content in concrete and other structural components at accelerator facilities. R.E. Welsh of the College of William and Mary collected wall core borings from the shielding walls and the vault surrounding the 600 MeV synchrocyclotron at the Space Radiation Effects Laboratory (SREL) in Newport News, VA. These borings were collected following removal of the synchrocyclotron and ancillary equipment after 15 years of operation. (We80) Four radionuclides were identified in the samples collected: ^{60}Co, ^{54}Mn, ^{22}Na, and ^{57}Co. Based on the concentrations and depth distribution of these radionuclides and the relative surface gamma exposure rates, ERC made an estimate of their total quantities in the concrete shield walls. The estimated totals in the SREL facility were: ^{60}Co, 30 mCi; ^{54}Mn, 45 mCi; ^{22}Na, 10 mCi; and ^{57}Co, 1 mCi. Ninety percent of the total induced activity was located in the shield walls of the room housing the synchrocyclotron.

Quantities of induced activity in components at the 155 MeV Orsay, France synchrocyclotron were measured 2 months following dismantling. (Ch79) The results of this analysis are shown in Table 3.6. The largest quantity of any nuclide in any of the structural components analyzed was 26 curies ^{54}Mn in the iron of the magnet poles and cylinder heads. The copper dee and anti-dee contained 6.1 curies of ^{57}Co and 6.9 curies of ^{58}Co. The stainless steel of the acceleration chamber contained 1.1 curies of ^{54}Mn. Total quantities of eight radionuclides identified are reported in Table 3.6.

The majority of the radioactive waste arises from decommissioning of an accelerator facility consists of the accelerator itself and its components. For ease of discussion, the radioactive waste will be divided into three classes: high level, moderate level, and low level. The highest levels of induced radioactivity can be expected in the components and materials either directly struck by the particle beam or in close proximity to points of beam interaction. Typical examples of these components are: targets, target holders, positioning mechanism for targets, beam stops, collimators, beam defining slits, extraction magnets and channels, beam pipes and local shields around targets and slits.

Moderate levels of induced activity can be expected in components of the accelerator and nearby auxillary items subjected to scattered beam or secondary particle irradiation. Components in this category include: electrostatic shields, cyclotron vacuum chambers, cyclotron magnet pole tips, magnet windings, bending and focusing magnets, synchrotron magnets and coils and linac drift tubes. (Op79a)

Cyclotrons, smaller synchrotrons and synchrocyclotrons have induced activity levels higher than the direct current machines. The

Table 3.6
Maximum activities remaining in Orsay 155 MeV synchrocyclotron components after 2 months of storage*

Material	Components	Mass (kg)	Maximum activity of radionuclides remaining after 2 months of storage (Ci)							
			Na-22	Cr-51	Mn-54	Co-56	Co-57	Co-58	Co-60	Zn-65
Copper	Dee, Anti-dee	300	--	--	1.2	2.3	6.1	6.9	0.93	0.77
Stainless Steel	Acceleration Chamber	5000	--	0.5	1.1	0.13	0.45	0.45	0.10	--
Iron	Magnet poles and cylinder heads	650000	--	--	40	--	0.16	0.16	1.3	--
Aluminum	Magnet Conductor	17000	0.05	--	--	--	--	--	--	--
TOTALS			0.05	0.5	28	2.4	6.8	7.5	2.3	0.77

*Reference: R. Choquet and F. Clapier (Ch79) induced activity will require remote handling of target probes, beam extraction components and other highly activated components. (Op79a) A cyclotron which has been operating for a 25-year period will have approximately 30% of the induced radioactivity remaining two years post-shutdown. Further radioactive decay is controlled by ^{60}Co. (Mu78)

The projected wastes associated with the dismantling of the Zero Gradient Synchrotron at Argonne National Laboratory are shown in Table 3.7. The ring magnet steel comprises more than 80% of the radioactive wastes from the synchrotron facility. Recycling of these materials would reduce the waste volume greatly. (Op79c)

The results of a radiation survey at the Cambridge Electron Accelerator Synchrotron are shown in Table 3.8. These radiation levels were measured at the time of shutdown. Activity levels 2 to 20 times background were measured in the copper and steel of the magnets following removal from the vacuum chambers. Levels greater than 2 times background were identified in the RF cavities, straight sections and vacuum chambers. (Op79c)

The 60-inch cyclotron at Argonne National Laboratory is estimated to have a mass of 880 tons of radioactive material out of a total mass of 6100 tons. (Op79a) The larger electron linear accelerators and synchrotrons will have induced activity similar to the above units except that target stations, beam switchyards and beam dumps will have higher levels and require additional remote handling. (Op79a)

Radiation levels were measured at the NASA-Space Radiation Effects Laboratory in Newport News, VA in September 1978, following shutdown in August. Components in the vacuum box (e.g. dees, platform target) had very high exposure rates (1-5 R/hr). The magnet hall and target areas were close to background (<3 mR/hr) except for magnets and hot spots which had readings between 10-50 mR/hr. Steel and concrete Kirksite blocks at the south end of the cyclotron vault had exposure levels of 10-50 mR/hr. The synchrocyclotron and ancillary equipment were transferred to

Table 3.7
Estimated wastes associated with the dismantling of the ZGS (Op79c)

Item Description	Waste Amount (ton) Radioactive	Nonradioactive
Ring		
Magnet steel	4787	
Coils	64.2	
Vacuum chamber	1.8	
Ring supports	60	
Operating floor	559	
Cables	126	
Accessory equipment	70	
Straight sections	62	
Concrete	38	
Injector		
High-voltage terminal	0.2	
High-voltage power supply		2
High-voltage-terminal room		20
Beam line	23	
Linac	41	
Linac accessories		133
Miscellaneous	10	25
Center Building		
Machinery		570
Piping		190
Power Building		
Motor-generator set		540
Spare shaft		30
Machinery		92
Cables		3.5
Control Room		
Machinery and cables		120
Total[a]	5842.2	1725.5

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[a] The number of significant figures shown is for computational accuracy and does not imply precision to the nearest ton.

Table 3.8

Survey of radioactivity in the Cambridge Electron Accelerator synchrotron as of June 2, 1973[a]
(Op79c)

Circular Tunnel	Exposure Rate (mR/h)
Upstream end of straight section 5:	1
Midway along beamrun portion from inner wall of circular tunnel to straight section 28:	2
All the rest of the circular tunnel (including target area, bypass, beamrun 5, store of spare ceramic and epoxy vacuum chambers, old ARCO linac):	0
Linac Tunnel	
Junction between waveguides 2 and 3:	30
4 and 5:	10
Immediately downstream from waveguide 3:	10
Immediately upstream of, also north of, also downstream from, converter assembly:	100 [b]
Fittings downstream from waveguide 5:	70 [b]
Several locations along east beamrun from those fittings to the concrete wall at down stream end of tunnel:	70
On the floor beneath above-mentioned fittings:	5 [b,c]
On the floor 16 in. east and 30 in. north of center of converter:	7 [b,c]
On north wall directly opposite (4 ft. north of) center of converter:	1.5
All the rest of linac tunnel:	Small compared to above
Synchrotron Radiation Room	Zero everywhere

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[a] From attachment to letter from William A. Shurcliff, Radiation Safety Officer, CEA, to Philip Thompson, AEC-Cambridge, MA, 8 June 1973.

[b] These levels were found to be unchanged within 20% three days later.

[c] Most of this originated in the beamrun, not the wall or floor.

Brookhaven National Laboratory (BNL) for reuse. (BNL Internal Memorandum from R. Casey to R. Rau, 10/9/78)

Low levels of induced activity (or in some cases no induced activity) should be expected in the building housing the accelerator facility and other items subject to low level neutron irradiation. Examples of items in this class include: accelerator vault concrete floor and walls; steel and concrete support structure; cyclotron steel magnet yokes; iron, concrete and lead shielding blocks; materials in underground vaults; and earth surrounding the underground vaults. (Op79a) During the decommissioning of the Carnegie-Mellon synchrocyclotron, detectable levels of induced activity were identified which necessitated removing a layer of concrete several inches thick from the floor. (Mu78)

Direct current machines generally have induced radioactivity in beam line components and the accelerator column. In addition, small electron linear accelerators (i.e. medical linacs and betatrons) have very low probabilities of induced radioactivity in components. Less than 0.5 % (or 0.3 tons) of the components of the Tandem Van de Graaff accelerator at Argonne National Laboratory are radioactive. Only 0.1% of the total mass, or 0.1 tons of material, of the 22 MeV Linac at Argonne is estimated to be radioactive. (Op79a)

Three major radiologic problems are involved with the operation of neutron generators. Activation of materials around the generator, the shielding of the neutrons and the release of tritium from the target are those problems most likely to be encountered with a 15 MeV unit. (Br71) However, Mundis et al. reported that neutron generators have very low levels of activation. (Mu78) The primary contaminant problem is ^3H which often is found in the pumps, static components, and exhausts from such a facility. (Nel69)

3.2.2. Physical Characteristics

Early accelerators were simply dismantled and their components reused for other purposes or sold for scrap. The beam energy and intensity was generally very low, so that any induced activity should be detectable using sensitive measuring techniques. (Mu78)

Radioactive wastes generated as a result of present day decommissioning of an accelerator facility consist mainly of large structural components. A large fraction of these structural components may be used at other accelerator facilities as shielding or in experiments.

The decommissioning of the University of Rochester synchrocyclotron in the early 1970's identified five major structural components to be dismantled (Op79c):

- Magnet Frame consisting of 6 large steel-carbon forgings, studs, nuts and washers: 8.3 tons
- Magnet Poles: 160 tons
- Pole Tips: 27 tons
- Exciting Coils from around each magnet pole
- Vacuum tank frame

Approximately 1000 tons of steel from this facility were sent to Fermi National Accelerator Laboratory in Batavia, IL in 40 ton sections for use in experiments. (Op79c)

A major advantage can be achieved in the dismantling of cyclotrons if the magnet structure has been assembled on site by lamination of heavy plates. This allows separation of the plates for disassembly and handling. However, if the magnet has been constructed of large forgings it may be necessary to cut it into smaller pieces before removal. (Op79c)

During the dismantling of the Carnegie-Mellon Synchrocyclotron at Saxonburg, PA, in 1973, magnet removal posed a major problem which led to cutting the unit into 16 pieces. The 16 pieces were then disposed of by shipment to the Massachusetts Institute of Technology (MIT), Los Alamos Scientific Laboratory (LASL), BNL and the Maxey Flats waste disposal sites. Decommissioning the Saxonburg facility generated approximately 360 m^3 of radioactive waste materials, equipment, and supplies; approximately 95%

consisted of iron and copper. Exposure rates at the copper dees and the steel pole tips were several R/hr in November 1968 when the site was shut down. In January 1973, the magnets had exposure rates of 175 mR/hr and the irradiated copper 430 mR/hr. (Op79c)

Wastes from the direct current machines generally consist of light structural steel and pose negligible problems in dismantling and disposal. (Op79a)

3.2.3. Chemical Characteristics

Solutions used to remove surface contamination generally consist of acids (e.g. HCl) or complexing agents (e.g., EDTA). The chemical form of the waste may be an important factor affecting the transport of radioactive materials in the environment following disposal. However, most of the residual radioactivity in accelerator facilities will be in the form of activated components rather than surface contamination. Hence, the volume of decontamination solution may be quite low for these facilities.

Chemical wastes may present a potential non-radiological health and safety problem associated with the decommissioning of an accelerator. Chemically toxic materials possibly present at a facility include beryllium, cadmium, lead, mercury, and others which will require hazard evaluation and appropriate control measures.

3.2.4. Handling Considerations

During the dismantling of an accelerator, external radiation exposure poses the major hazard. Two to three weeks following shutdown of the UCLA 22 MeV cyclotron, exposure rates exceeding 100 R/hr were measured at the accelerator surface. Conversely, at the University of Washington 40 MeV cyclotron, exposure rates on the order of 100-200 mR/hr post-operation have been measured. (Op79c) Radiation measurements should be made at each site to determine the need for special handling methods and safety measures and to generally characterize the radiation ennvironment. Based upon these measurements, the appropriate protective clothing and equipment can be supplied and the necessary working limits imposed. During any clean-up or dismantling operations, appropriate precautions should be taken by workers to prevent inhalation or ingestion of the dust resulting from any dust-producing operations. Work involving close spaces, heavy rigging and other stress will require a review of the industrial-safety aspects and will require appropriate surveillance and control. (Op79c)

Two radiological considerations enter into the decommissioning of particle accelerators. One consideration is the radiation dose that decommissioning personnel receive in the course of any decommissioning operations. The second consideration is potential radiation exposure to the general population resulting from: 1) transport and disposition of the radioactive waste in onsite or offsite retrievable storage or offsite waste disposal, and 2) reuse of accelerator components, materials, or structures containing induced radioactivity. (Op79c) The same factors governing the likelihood of induced radioactivity at an accelerator facility also determine the magnitude of the radiological problem at a facility.

The main source of radiation exposure during dismantling work is in the component classified as the "target." In addition to this area, other components can pose potential problems. Cooling water systems may accumulate and concentrate activated corrosion products. Vacuum or ventilation systems may be similarly contaminated. Accelerators used in isotope production or for the acceleration of radioactive ions (e.g., H-3) or used with radioactive target materials (e.g., TRU elements) also present a potential hazard due to surface contamination on components. (Op79c) During the dismantling operations of cyclotrons, synchrotrons, and synchrocyclotrons, available remote-handling capabilities should be used for removal of target probes, beam extraction components, and other highly activated materials. (Op79a)

A variety of dismantling operations will require some type of worker hazard-control measures. Typical examples include such operations as sawing and cutting of metal, and scarfing, cutting or jack hammering of concrete. The radiological health physics requirements for such operations may include: respiratory protection to prevent inhalation, and/or local ventilation with filtered exhaust and to prevent the spread of loose contamination. Protective clothing and some contamination control measures will be required at all facilities. (Op79c)

4.0 GENERIC FACILITY DESCRIPTION

In this section, the information described in the previous section is generalized to generic accelerator facilities. It is recognized that machines vary greatly within the individual classes used in our study. Generic facility descriptions can be made based upon an inspection of our final listing of accelerator facilities. Based on this inspection, generic accelerators have been selected representing the average facilities in the survey for each accelerator category, as follows:

60-Inch Cyclotron
20 MeV Tandem Accelerator
15 MeV Linear Accelerator
5 MeV Van de Graaff Generator
2 MeV Cockroft-Walton Machine
500 MeV Synchrocyclotron
25 MeV Betatron
10 MeV Neutron Generator
500 MeV Synchrotron

These accelerators typify those identified in each category in this study. However, individual facilities span a very broad range of energy, size, and other characteristics. Some general characteristics and observations regarding these accelerator facilities are presented in the following sections.

4.1 Operating Lifetime

For a variety of reasons, relatively few first beam dates are available for the accelerator units listed in Appendix A. From our review of the available information, the average operating lifetime of an accelerator facility has been assumed to be approximately 20 years. In actual operating experience, units have been decommissioned at the end of five years and some have been operating for more than 35 years. The accelerators used for the longer periods of time are generally large units which have been constructed with special capabilities. Our estimate of the average operating lifetime, 20 years, is used with the assumption that the technology will continue to advance, and keeping the units on line for a longer period of time would be both technologically and economically unjustified. In any case, the projected schedule for facility shutdown or decommissioning must be interpreted as a rough approximation at best.

4.2 Waste Characaterization

To identify induced radionuclides at an accelerator facility, core borings and samples can be collected and analyzed. Accelerator shielding and components, which include the magnets, targets, cooling water, and even the ground water close to the accelerator building may all have induced radioactivity to some degree.

As noted previously, the principal radionuclides of concern are ^{60}Co, ^{22}Na, and ^{55}Fe. There is an initial rapid decay of short-lived radionuclides in components followed by slower decay of the longer-lives radionuclides. In principle, all nuclides with atomic mass and number equal to, or less than the total of the target numbers plus projected nuclei can be produced as induced activity at an accelerator facility. Many of these have such short half-lives that they do not pose a radiological problem. Exposure rates are reduced by approximately a factor of 2 in the first 2 hours and by another factor of 2 within the next 50 hours. (ICRU78)

The highest levels of induced radioactivity will occur in those materials struck directly by the particle beam or close to points of beam-material interaction. Moderate levels of induced activity will occur in the accelerator and auxilliary items in the vicinity. Low levels of activity (and for a small accelerator, background levels) will be found in the concrete and other construction materials housing the accelerator.

The generic direct current machine will have the highest levels of induced activity in the beam line components and the accelerating columns. (Op79a) Other components can be used for scrap material. There is no need to anticipate building decontamination procedures unless surface contaminants are identified. (Op79c)

The large electron linear accelerators and synchrotron units will have moderate levels of induced activity in the majority of the components.

Smaller electron linear accelerators (and betatrons) used for medical purposes have very little likelihood of significant levels of induced activity in components. It is also assumed that this will be true of the generic neutron generator facility. Again, building decontamination is not necessary unless surface contaminants are identified. (Op79c)

The quantity of wastes resulting from decommissioning of the generic facilities increases dramatically with increasing particle energy. The physical wastes generated as a result of decommissioning of an accelerator facility consist mainly of large structural components. A large portion of these will be sent to other accelerator facilities as shielding or for experiments.

4.3 Decontamination and Decommissioning Alternatives

Those facilities being planned and constructed should have potential D&D alternatives reviewed prior to start of operations. If this is done, many potential problems can be eliminated or minimized, such as inaccessible components, induced radioactivity in poorly selected components, and commitment of scarce resources. (Op79a)

The major radiological concern at the time that operations are terminated at an accelerator facility is the level of induced radioactivity in the accelerator unit and its environs. The residual radiation levels at accelerator facilities are primarily due to neutron induced activation products and spurious beams in the accelerator itself and the associated shielding material. (Op79c)

A radiological survey of the unit housing the accelerator can be planned and conducted once the unit is shut down. Routine radiation surveys are conducted during accelerator shutdown periods to monitor induced activity levels. Alternatives for decontamination and decommissioning of the accelerator facility can be examined based upon the results of the radiation survey. The smaller medical therapy units and industrial linear accelerators which employ electrons of low energies and low current at staggered times, generally pose little residual radiological hazard. Conversely the large research accelerators may pose a major radiological problem due to the acceleration of particles to higher energies using a higher beam intensity, and more frequent use of the unit.

The basic alternatives involved in decommissioning of particle accelerators include (Op79c):

- Mothballing,
- Entombment,
- Dismantling with storage of potentially reusable or salable components until induced radioactivity has decayed to safe levels,
- Dismantling with disposal of all materials as radioactive wastes, or
- Transferring or reusing the unit (or a portion of it) intact at another site.

Mothballing involves only a general clean-up around the accelerator and is designed to allow residual induced radioactivity to decay with minimal initial commitment of funds. (Op79a) It involves packaging all loose contaminated materials for appropriate disposal and locking entrances to the building. Mothballing is especially appropriate for situations where the reuse of accelerator components is foreseen. The potential reuse of some metals (iron, copper, and steel) can be greatly increased by allowing the facility to remain in a mothballed stage for a number of years to allow those radionuclides with short half-lives to decay. Mothballing can be used in conjunction with any of the other D&D options. It appears to be most feasible with facilities which have moderate to high levels of induced activity.

Entombment is similar to mothballing, except all entrances are sealed with concrete instead of merely blocked. Concrete blocks up to a thickness of 3 feet may be used for this purpose. This option is rarely optimal due to the relatively localized, short decay time of most induced activity at an accelerator facility. Furthermore, entombment would unnecessarily prohibit future use of the site. (Op79c) In only one instance, at high energy accelerator facilities, entombment of the target area may be a desirable option. (Op79a)

Mothballing and entombment have the advantage of not generating any wastes and not requiring any major construction activities. The building or unit is left to stand in an undisturbed or security-controlled area. These approaches can be used to greatest advantage in cases where the materials are contaminated primarily with short-lived radionuclides and which are located within a security-controlled area. When longer-lived nuclides are present (e.g. Co-60, Na-22, Fe-55) mothballing or entombment for longer periods may be required (e.g. perhaps 20 years for Co-60).

Items which are slightly activated can be placed in retrievable storage for potential reuse following dismantling of the facility or for sale as scrap following decay of induced activity. These are items in which only localized 'hot areas' of radiation have been produced as a result of beam-materials interactions. The storage period should be long enough to allow the induced radioactivity to decay to prescribed levels. In most cases the radionuclide with the limiting life is Co-60 (5.27 year half-life). Components that would typically be stored for potential reuse include: magnet sections, copper coils and other massive structural pieces. Disposal of these components or wastes might entail significant and unnecessary depletion of natural resources, and may often be economically unjustified. Those components with no reuse potential can be shipped to a radioactive waste burial facility, or, if proven to be uncontaminated, sold as scrap. Those units which are either technologically too old to be economically salvaged or those which have induced activity to the extent that reclamation is not economically feasible usually fall into this category.

Alternatively, an intact unit may be transferred to another site for future use. This is done in some cases with smaller, technologically obsolete machines, such as particle injectors, which may find application as an improved injector or proton booster for a larger accelerator. (Op79a) In some cases only certain radioactive components will be selected for reuse at another site where further component activation will occur. (Op79c) For example, an older proton linac injector was shipped from one site to another site for use as an improved injector. (Op79a) The transfer option is chosen based upon the needs of other accelerator facilities at the time of decommissioning.

4.4 Recyclable Components

Components from a decommissioned accelerator facility can often be used at another site. It would be advantageous for recycling to allow the facility to remain in a mothballed state for some period of time prior to removal of the components. This would allow maximum recycling with a minimal amount of manpower and economic expenditures.

Natural resources, such as copper and iron metals, should be recycled to the greatest extent possible. A vast majority of components from a decommissioned accelerator contain only small amounts of induced activity. As discussed in the previous section, there is an economic as well as an environmental incentive to recycle these components when possible. In the past large pieces of steel and concrete have been claimed by other accelerator facilities and reused, sometimes serving as additional shielding. Many components have in the past also been sold for scrap if they are not requested for recycling. (Pet79, Mu78)

Electron linear accelerators, in some cases, are composed of easily dismantled modules. Some modules, such as the klystrons and vacuum pumps can sometimes be reused. The water-cooling modules may be used in future experimental set-ups. (Op79a) The modulator, amplifier power supply, and auxiliary power supply modules are considered surplus unless there is an immediate apparent use. Table 4.1 contains a listing of some typical recyclable linear accelerator items.

Generally, the salvage and recycle value of a tandem accelerator is no more than that of scrap unless the machine can be transferred in its entirety. (Op79a) These are small units compared to the larger, higher energy accelerator units used at research institutes. Negative ion sources

Table 4.1 Possible Sequences of Decommissioning Activities (Op79c)

Entomb
Mothball
Mothball | reuse entire accelerator
Mothball | dismantle | waste[a]
Mothball | dismantle | recycle
Mothball | dismantle | scrap[b]
Mothball | dismantle | storage | waste
Mothball | dismantle | storage | recycle
Mothball | dismantle | storage | scrap
Mothball | dismantle | mothball
Dismantle | mothball
Dismantle | storage
Dismantle | storage | waste
Dismantle | storage | recycle
Dismantle | storage | scrap
Dismantle | waste
Dismantle | recycle
Dismantle | scrap
Dismantle | reuse entire accelerator

---

[a] Waste is material considered radioactive and buried in a commercial nuclear-waste burial ground.

[b] Scrap is material considered no longer radioactive.

will have many components useful elsewhere at a large research facility and can be reused. (Op79c)

Certain accelerator parts may have to be machined in order to salvage non-contaminated reusable metals. (Pr76) This poses a potential for external exposure to workers and possible inhalation if proper respiratory protection measures are not taken. There will be cases where the benefit of recycling a component will need to be weighed against the radiation exposure of workers involved.

5.0 FACILITY AND SITE-SPECIFIC ISSUES

5.1 On-Site Disposal

Most accelerator facilities presently use a commercial radioactive waste disposal service for disposal of contaminated wastes. Some of the earlier accelerator facilities disposed of materials by on-site burial. This procedure was followed by Carnegie-Mellon University at the Saxonburg, PA Research Facility. Eleven individual burials in 50-gallon drums were made on the site in addition to disposal in a concrete-covered pit. The buried wastes were exhumed with a backhoe and air hammer and were shipped to the Maxey Flats, KY burial site. (Op79c)

5.2 Long-Lived Induced Activity

At accelerator facilities, the primary contamination problem is induced activity in the accelerator and structural components. In reviewing the list of radionuclides commonly activated at an accelerator facility (Table 3.4) the principal long-lived radionuclides are Co-60, Na-22 and Fe-55. Other induced radionuclides have half-lives generally less than one year. After a period of approximately 20 years, the Co-60 in a 600 MeV synchrocyclotron facility would decay to levels at or near 2 times background.

5.3 Dismantling Procedures

During the dismantling and demolition of the Cambridge Electron Accelerator at Harvard University a problem was encountered of importance for facilities in urban areas. The poured concrete walls in the underground tunnel were five to six feet thick in some areas, and, during the demolition, vibration from the wrecking ball caused some neighboring homes to shake. This led to a modification of the decommissioning plan; the tunnel walls were left intact and the tunnel was filled with dirt. (Op79c)

5.4 Assembly Procedures

Another major problem which has been encountered in past decommissioning operations of cyclotrons concerns magnet structure assembly. The primary concern is if the magnets had been assembled on site by lamination of heavy plates or if the magnet was constructed of large forgings. Problems could be encountered in removing very large sections which may require special alterations of the facility. (Op79c)

6.0 SUMMARY AND CONCLUSIONS

Information has been compiled describing active and inactive particle accelerators in the United States. The 1042 active and 107 inactive units and their locations have been listed in Appendix A. It is probable that these numbers may underestimate the actual numbers due to deficiencies in the data available.

Table 6.1 presents a summary of the accelerator facilities identified in this study. Of this total, approximately 40% of the units are linear accelerators, primarily small units used in medical and industrial applications. Direct current machines, primarily Van de Graaff and Cockroft-Walton accelerators, also comprise a large share (about 20%) of the total units identified. The "miscellaneous" category contains those accelerators for which detailed descriptions of the type of accelerator were unavailable and these constitute about 20% of the total accelerator facilities.

The data compiled in Appendix A has been used to estimate potential volumes of radioactive waste generated during decontamination and decommissioning of accelerator facilities. These estimates are based upon numerous assumptions described previously.

Table 6.1 Summary of Accelerator Facilities

Accelerator Type	Total Units	Active Units
Linear Accelerators	422	411
Direct Current Machines	218	193
Betatrons	72	50
Cyclotrons	82	60
Synchrotrons	30	17
Synchrocyclotrons	8	2
Tandem Accelerators	32	27
Neutron Generators	26	24
Ion Implanters	23	23
Cohesive Binders	31	30
Storage Rings	2	2
Miscellaneous*	203	203
Total	1149	1042

*This category is used for those states which sent lists of facilities but were unable to give detailed descriptions of the type of accelerator, and, in some cases, the number of accelerators at a site. Therefore, the number of accelerators in this category is subject to significant uncertainty.

The approximate mass and volume of radioactive waste produced at each accelerator facility of different types are shown in Table 6.2, based upon the data of Mundis et al. (Mu78) It is readily apparent that these estimates span a very broad range, and that use of these values for a particular accelerator may be quite tenuous.

As described in Section 4.1, a duration of 20 years has been asssumed on the average operating lifetime for accelerator facilities. All presently active units are assumed to be shut down by the year 2000. Those units with no information on the first beam date were pooled; 50% of these accelerators are assumed to be decommissioned in the 1980's and the remaining 50% to be decommissioned in the 1990's.

Based upon these data and assumptions, estimates of the potential radioactive waste produced from the decontamination and decommissioning of each accelerator category between the years 1940 and 2000 have been computed. The results of this analysis are shown in Tables 6.3-6.8 for each accelerator type and for each decade. Table 6.9 presents a total of the radioactive wastes resulting from decontamination of federal and non-federal accelerator facilities for the years 1940-2000. Table 6.10 is a summary of the wastes produced from the decommissioning of accelerator facilities between 1940-2000.

While the numerical values in these tables are somewhat speculative, it is possible to make several general observations. A trend of increasing amounts of waste is evident between 1940 and 1970 as accelerators gained wider usage and older units were decommissioned. Furthermore, the volume of radioactive waste is dominated by that from very large facilities, primarily proton synchrotrons, heavy ion linear accelerators and larger cyclotron units. As shown in Table 6.2, the volume of radioactive waste from most other facilities is insignificant compared to the volumes of radioactive waste from these facilities. In fact, the estimate of radioactive waste volumes for each 10-year period between 1960 and 2000 is dominated by the decommissioning of one or more of the very large accelerator facilities.

Table 6.2 Estimates of Mass and Volume of Radioactive Waste from Accelerator Facilities*

Accelerator Type	Estimated Mass of Radioactive Waste - (tons per Accelerator)	Estimated Volume of Radioactive waste - (m^3 per Accelerator)
Electrostatic Accelerators (Op79b)	0.17	--
Cyclotrons < 20" diameter e^- - Linacs < 600'	≤ 30	≤2
Cyclotrons 20-50"	30-250	≤60
Cyclotrons 50-100 e^- - linacs ≥ 600' e^- - synchrotrons	250-800	60-200
Cyclotrons > 100"	800-2300	200-570
p-Synchrotrons 60'-100' diameter	2300-16,500	570-4000
p-Sychrotrons > 200' p-Linac > 500'	16,500-220,000	4000-57000

*After Mundis et al., except as noted.

Table 6.3

Potential Radioactive Waste Produced From D&D of Betatron Facilities

	Federal Facilities		Non-Federal Facilities	
Date	Mass (tons)	Volume ($\times 10^3$ m^3)	Mass (tons)	Volume ($\times 10^3$ m^3)
1940-1950	--	--	--	--
1951-1960	≤ 150	≤ 30	100-350	80-300
1961-1970	150-500	90-300	400-1000	300-700
1971-1980	150-400	80-300	150-400	80-200
1981-1990	≤ 25	≤ 4	450-1500	100-500
1991-2000	≤ 25	≤ 4	450-1000	200-600
TOTALS	400-1000	200-600	2000-5000	800-2000

Table 6.4

Potential Radioactive Waste Produced from D&D of Synchrocyclotron Facilities

Date	Federal Facilities		Non-Federal Facilities	
	Mass (tons)	Volume ($\times 10^3$ m^3)	Mass (tons)	Volume ($\times 10^3$ m^3)
1940-1950	--	--	--	--
1951-1960	--	--	--	--
1961-1970	350-1000	300-700	25-250	20-200
1971-1980	1000-2000	500-1000	--	--
1981-1990	350-1000	500-2000	350-1000	300-700
1991-2000	200-500	200-400	--	--
TOTALS	2000-5000	2000-4000	400-1000	300-900

Table 6.5

Potential Radioactive Waste Produced from D&D of Cyclotron Facilities

	Federal Facilities		Non-Federal Facilities	
Date	Mass (tons)	Volume ($\times 10^3$ m^3)	Mass (tons)	Volume ($\times 10^3$ m^3)
1940-1950	15-100	9-80	15-100	9-80
1951-1960	100-350	80-300	--	--
1961-1970	250-1000	200-600	300-1500	200-900
1971-1980	150-500	90-300	350-15000	300-900
1981-1990	500-2500	600-2000	1000-4500	800-4000
1991-2000	200-500	100-800	1000-3500	800-3000
TOTALS	1000-5000	1000-4000	2500-25000	2000-9000

Table 6.6

Potential Radioactive Waste Produced from* D&D of Linear Accelerator Facilities

	Federal Facilities		Non-Federal Facilities	
Date	Mass (tons)	Volume ($\times 10^3$ m^3)	Mass (tons)	Volume ($\times 10^3$ m^3)
1940-1950	--	--	--	--
1951-1960	--	--	--	--
1961-1970	≤25	≤4	10000-200000	10000-100000
1971-1980	--	--	≤35	≤6
1981-1990	10000-100000	5000-7000	2000-3000	500-1000
1991-2000	10000-100000	5000-70000	10000-100000	5000-35000
TOTALS	20000-2000000	10000-100000	20000-300000	15000-150000

*Includes neutron generators and "miscellaneous" accelerator facilities.

Table 6.7

Potential Radioactive Waste Produced from
D&D of Synchrotron Facilities

Date	Federal Facilities		Non-Federal Facilities	
	Mass (tons)	Volume ($\times 10^3$ m^3)	Mass (tons)	Volume ($\times 10^3$ m^3)
1940-1950	--	--	--	--
1951-1960	1000-10000	800-5000	250-500	200-500
1961-1970	--	--	500-2000	400-1000
1971-1980	1000-10000	700-5000	--	--
1981-1990	10000-100000	6000-80000	350-25000	2000-20000
1991-2000	3000-25000	2000-20000	25000-150000	8000-90000
TOTALS	15000-150000	10000-100000	30000-200000	10000-100000

Table 6.8

Potential Radioactive Waste Produced from D&D of Direct Current Machines[*]

	Federal Facilities	Non-Federal Facilities
Date	Mass (tons)	Mass (tons)
1940-1950	--	0.1
1951-1960	0.2	0.2
1961-1970	0.3	1.5
1971-1980	0.2	1
1981-1990	2	10
1991-2000	1	5
TOTALS	4	20

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[*] Includes tandem accelerators.

Table 6.9

Potential Radioactive Wastes Produced from D&D of All Accelerator Facilities

	Federal Facilities		Non-Federal Facilities		Total	
Date	Mass (tons)	Volume ($\times 10^3$ m^3)	Mass (tons)	Volume ($\times 10^3$ m^3)	Mass (tons)	Volume ($\times 10^3$ m^3)
1940-1950	15-100	9-80	15-100	9-80	30-200	20-200
1951-1960	1500-1(4)[a]	900-5000	350-1000	300-800	30-200	1000-6000
1961-1970	1000-2500	600-2000	1.5(4)-2(5)	1(4)-1(5)	1.5(4)-2(5)	1(4)-1(5)
1971-1980	2000-2(4)	1000-6000	500-1.5(4)	400-1000	2500-3.5(4)	1000-7000
1981-1990	2(4)-2(5)	1(4)-2(5)	1(4)-4(4)	3000-30000	3(4)-2.5(5)	1(4)-2(5)
1991-2000	2(4)-2(5)	7000-90000	2(4)-2.5(5)	10000-2(5)	3.5(4)-4(5)	2(4)-3(5)

[a] 1(4) indicates 1×10^4

Table 6.10

Potential Radioactive Wastes Produced from
D&D of Accelerator Facilities from 1940-2000

	Mass (tons)	Volume (x 10^3 m^3)
Linear Accelerators	40000-500000	30000-300000
Synchrotrons	40000-400000	20000-200000
Cyclotrons	3500-30000	3000-10000
Synchrocyclotrons	2000-5000	2000-5000
Betatrons	2000-5000	1000-2000
Miscellaneous Units	1000	100
Direct Current Machines	20	70
Neutron Generators	300	40
Tandem Accelerators	2	8
Ion Implanters	--	--
Cohesive Binders	--	--
Storage Rings	--	--
TOTAL	$\leq$1000000	$\leq$500000

The estimates in Tables 6.3-6.8 can be considered upper and lower bounds of the potential radioactive waste from decommissioning of accelerator facilities. These estimates have been made using the estimated waste per accelerator for each of the facilities listed in the appendix, and projection of a simplistic timetable for decommissioning each of these units. In all cases, we have assumed that all radioactive material will be discarded as radioactive waste.

A more realistic approach for most, if not all of the facilities examined would be mothballing the facilities until the radioactivity decays to safe levels. Moreover, it is likely that many components could be reused in other facilities. This would reduce the waste volumes significantly.

Based on this study, radioactive waste from accelerator decommissioning represents a significant volume and requires proper disposal. The current trend of increased use of accelerators by individual and industrial customers will lead to an increased need for disposal of radioactive wastes resulting from future accelerator decommissioning.

References

Al46 Alvarez, L.W., 1946, "The Design of a Proton Linear Accelerator," Physical Review 70, 799.

Be58 Behman, Gerald Al., 1958, "Particle Accelerators," University of California, Radiation Laboratory, Berkeley, CA, January 1, 1958.

Bo61 Boom, R.W., K.S. Toth, A. Zucker, 1961, "Residual Radiation of the LRL 184-Inch Cyclotron," Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-3158.

Br71 Broerse, J.J., A.C. Engels, J.S. Groen, 1971, "Life-Time of Tritium Targets and Release of Tritium from D-T Nuetron Generators," in The International Journal of Applied Radiation and Isotopes, Volume 22, Pergamon Press, pp. 486-489.

Bu69 Burrill, E.A., 1969, "The Expanding Use of Particle Accelerators in Research, Medicine and Industry: A Statistical Review," in Proceedings of the Second International Conference on Accelerator Dosimetry and Experience, Stanford, CA, November 5-7, 1969, CONF-691101.

Ca78 BNL Memo from R. Casey to R. Rau, 10/9/78, re: SREL radiation component levels as a result of 9/14/78 survey.

Ce79 Cehn, Joel, August 1979, "A Study of Radioactive Airborne Effluents from Particle Accelerators," Prepared for U.S. Environmental Protection Agency by Teknekron Research, Inc., McLean, VA. ORP/TAD 79-12.

Ch79 Choquet, R. and F. Clapier, 1979, "Data on the Activation and Dismantling of the 155 MeV Synchrocyclotron of the Institute of Nuclear Physics at Orsay," Radioprotection, 14(2), p. 81.

Co76 Cohen, S.C., et al., December 1976, "Evaluation of Occupational Hazards from Industrial Radiation: A Survey of Selected States," U.S. Department of Health, Education and Welfare, Publication No. (NIOSH) 77-142.

ERC82a Evaluation Research Corporation, 1982, "Characterization of Contaminated Nuclear Sites, Facilities and Materials (Radioisotope and Radiopharmaceutical Manufacturers and Suppliers)," Oak Ridge, TN.

ERC82b Evaluation Research Corporation, 1982, "Characterization of Contaminated Nuclear Sites, Facilities and Materials (Independent Research and Development Institutes)," Oak Ridge, TN.

Go76 Gollon, P.J., August 1976, "Production of Radioactivity by Particle Accelerators," in IEEE Transactions in Nuclear Science, NS-23(4).

Gr81 Personal communication, Dr. Graham Grundy, American College of Radiology, Patterns of Care Study, November, 1981.

Ho67 Howard, F.T., October 1967, "High Energy Accelerators - 1967," Accelerator Information Center, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-AIC-1.

Ho69 Howard, F.T., September 1969, "Isochronous Cyclotrons - 1969," Prepared by Accelerator Information Center, Oak Ridge National Laboratory, Oak Ridge, TN for The International Cyclotron Conference, Oxford, England, September 17-19, 1969.

Ho74 Howard, F.T., December 1974, "Tandem Accelerators - 1973-74," Accelerator Information Center, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-TM-4934.

ICRP59 International Commission on Radiological Protection (ICRP), 1959, Report of Committee 2 on Permissible Dose for Internal Radiation, Publication 2, (New York: Pergamon Press).

ICRP77 International Commission on Radiological Protection (ICRP), 1977, Annals of the ICRP, Publication 26, (New York: Pergamon Press).

ICRU78 International Commission on Radiation Units and Measurements (ICRU), 1978, "Basic Aspects of High Energy Particle Interactions and Radiation Dosimetry," ICRU Report No. 28.

Ka64 Karetnikov, D.V., I.N. Slivkov, V.A. Teplyakov, A.P. Fedotov, B.K. Shembel, March 1964, "Linear Ion Accelerators," USAEC, Division of Technical Information, AEC-tr-6229.

Ke41 Kerst, D.W., 1941, "The Acceleration of Electrons by Magnetic Induction," in Physical Review 60, 47.

Ma78 Martin, John A., 1978, "Cyclotrons - 1978," Holifield Heavy Ion Research Facility, Oak Ridge National Laboratory, for The 8th International Conference on Cyclotrons and Their Applications, Indiana University, Bloomington, IN, September 18-21, 1978.

Mu78 Mundis, R.L., M.J. Kikta, G.J. Marmer, J.H. Opelka, J.M. Peterson, B. Siskind, 1978, "Health Physics Considerations in Accelerator Decommissioning and Disposal," Argonne National Laboratory.

NBS70 National Bureau of Standards, June 1970, "Radiological Safety in the Design and Operation of Particle Accelerators," ANSI Subcommittee N43-4, NBS Handbook 107.

Op79a Opelka, J.H., J.M. Kikta, G.J. Marmer, R.L. Mundis, J.M. Peterson, B. Siskind, 1979, "A Decommissioning Plan for Particle Accelerators," Prepared for Decontamination and Decommissioning of Nuclear Facilities, American Nuclear Society, Sun Valley, ID, September 16-19, 1979. Argonne National Laboratory.

Op79b Opelka, J.H., G.J. Marmer, R.L. Mundis, J.M. Peterson, B. Siskind, June 1979, "Reutilization Potential of Accelerator Components: A Decommissioning Perspective," IEEE Transactions on Nuclear Science, NS-26 (3).

Op79c Opelka, J.H., R.L. Mundis, G.J. Marmer, J.M. Peterson, B. Siskind, M.J. Kikta, December 1979, "Particle-Accelerator Decommissioning," Argonne National Laboratory, ANL/ES-82.

Pa73 Patterson, H.W., and R.H. Thomas, 1973, Accelerator Health Physics, (London, England: Academic Press).

Pet79 Peterson, J.M., J.H. Opelka, R.L. Mundis, 1979, "Waste Management Considerations in Particle Accelerator Decommissioning," in Transactions of the American Nuclear Society 25th Annual Meeting, Volume 32, TANSAO 32 1-832.

Pr76 Price, K.W. and G.R. Holeman, 1976, "Health Physics Aspects of the Yale Heavy Ion Linear Accelerator Dismantling Project," in Proceedings of the Ninth Midyear Topical Symposium of the Health Physics Society, Denver, CO, February 9-12, 1976.

Re81 Personal communication, Henry Rechen, Deputy Director, Division of Electronic Products, Bureau of Radiological Health, December 1981.

Sh81 Personal communication, Heyward Shealy, South Carolina Department of Health and Environmental Control, Bureau of Radiological Health, November, 1981.

USBRH75 U.S. Bureau of Radiological Health, 1975, The Use of Electron Linear Accelerators in Medical Radiation Therapy, Overview Report No. 2. Market and Use Characteristics: Current Status and Future Terms.

USBRH77 U.S. Bureau of Radiological Health, 1977, Report of the State and Local Radiological Health Programs Fiscal Year 1977, HEW Publication No. 78-8034.

Va31 Van de Graaff, R.J., 1931, "A 1,500,000-Volt Electrostatic Generator," in Physical Review, 48, 315.

We80 Welsh, R.E. "A Determination of the Level of Activation Products in the SREL Wall," College of William and Mary, Williamsburg, VA.

APPENDIX A.
LIST OF ACCELERATOR FACILITIES

Linear Accelerators

Facility and Location	Number and Type (First Beam)	Reference
Abbott-Northwestern Hospital 810 E. 27th St. Minneapolis, MN 55407	1-20 MeV Linac	54
Agnes Raoul Glenn Memorial Radiation Therapy Center Crawford W. Long Memorial Hospital 25 Prescott St. Atlanta, GA	1-4 MeV Linac 1-12 MeV Linac	31
Alabama, University of Chemistry Dept. Lloyd/Montgomery Halls University, AL 35486	1-0.5 MeV Linac (1974)	52
Allenmore Community Hospital S. 19th and Union Tacoma, WA		26
Amerace Corporation Tri-County Industrial Park Piney Flats, TN	1-800 keV Linac	32
Argonne Cancer Research Hospital University of Chicago Chicago, IL	1-50 MeV e-Linac (1957)	5,22
Argonne National Laboratory Argonne, IL	1-22 MeV e-Linac (1969)	22
Argonne National Laboratory Linac Injector to ZGS Argonne, IL	1-50 MeV Linac (1963)	22,30
Arizona, University of (5 units) Radiation Oncology Department 1827 East Mabel Tucson, AZ 85724	3-4 MeV Linacs 1-18 MeV Linac 1-Deep Therapy Unit	15
Arizona Radiation Oncology, Ltd. 7555 East Osborn Rd. Scottsdale, AZ 85253	1-6 MeV Linac 1-Deep Therapy Unit	15 15
Arkansas, University of Fayetteville, AR		6

Facility and Location	Number and Type (First Beam)	Reference
Associates in Radiation Oncology, P.C. 10503 West Thunderbird Rd. Sun City, AZ 85351	1-6 MeV Linac	15
Atlas Foundry 3021 S. Wilkeson Street Tacoma, WA		26
Augusta Radiation Therapy Center University Hospital University Place Augusta, GA	1-4MeV Linac	31
Bannock Memorial Hospital Intermountain Cancer Center Memorial Drive Pocatello, ID	1-6 MeV Linac	46
Baptist Hospital Pensacola, FL	1-4 MeV Linac	10
Baptist Medical Center Jacksonville, FL	1-4 MeV Linac 1-20 MeV Linac	10 10
Baptist Medical Center Taylor Marion Columbia, SC	1-12 MeV Linac	34
Baptist Memorial Hospital 899 Madison Ave. Memphis, TN	1-4 MeV Linac 1-18 MeV Linac	32 32
Bartol Research Foundation of the Franklin Institute Swarthmore, PA		5
Battelle Northwest (5 units) Pacific Northwest Laboratory 1 Battelle Blvd. Richland, WA		26
Bay Memorial Medical Center Panama City, FL	1-4 MeV Linac	10
Bayfront Medical Center St. Petersburg, FL	2-6 MeV Linacs 1-20 MeV Linac	10 10
Bell Laboratories (2 units) Positive Ion Accelerator Allentown, PA		13
Bell Laboratories Positive Ion Accelerator Reading, PA		13

Facility and Location	Number and Type (First Beam)	Reference
Bishop Clarkson Memorial Hospital 44th and Dewey Avenue Omaha, NE 68105	1-6 MeV Linac	19
Bismarck Hospital 300 N. 7th Street Bismarck, ND		11
Blake, L. W., Memorial Hospital Bradenton, FL	1-4 MeV Linac 1-6 MeV Linac	10 10
Boca Raton Community Hospital Boca Raton, FL	1-4 MeV Linac 1-18 MeV Linac	10 10
Boeing Company (2 units) Plant #2 7755 E. Marginal Way Seattle, WA		26
Boeing Scientific Research Center (7 units) 1420 S. Trenton Street Seattle, WA		26
Bristol Memorial Hospital 209 Memorial Drive Bristol, TN	1-4 MeV Linac	32
Brookhaven National Laboratory Linac Injector to AGS Upton, NY *(50 MeV Linac injector sent to LBL to be used as Bevatron injector)	1-200 MeV Linac (1960) 1-50 MeV Linac Injector	5,22 22
Brooks-Williamette Corp. 1 S. Hill Street Bend, OR 97701		16
Brown University Providence, RI		5,22
Burlington Medical Center 602 N. 3rd Streeet Burlington, IA 52601	1-4 MeV Linac (1978)	57
California, University of Livermore, CA	1-35 MeV Linac (1959) 1-100 MeV Linac (1970)	22 22
California, University of Super-HILAC Berkeley, CA	1-Heavy Ion Linac (1971)	22

Facility and Location	Number and Type (First Beam)	Reference
California, University of Lawrence Radiation Laboratories Livermore, CA (*dismantled in 1970)	1-35 MeV e-Linac	22
California, University of (5 units) Radiation Laboratory Berkeley, CA (*30 Mev proton linac decommissioned in 1960)		5,22
California, University of (4 units) Radiation Laboratory Livermore, CA		5
California, University of Radiation Laboratory Site 300 Livermore, CA		5
Capital Area Radiation and Research Center 2600 East 19th St. Austin, TX	1-4 MeV Linac	44
CBI Nuclear Company 2700 Channel Ave. Memphis, TN	2-7.5 MeV Linacs	32
Cedars of Lebanon Hospital Miami, FL	2-4 MeV Linacs	10
Central Arkansas Radiation Therapy Institute, Inc. Markham at University P. O. Box 5668 Little Rock, AR		6
Central Kentucky Radiation Oncology Center 1517 South Limestone Lexington, KY	1-4 MeV Linac	12
Central Maine Medical Center 300 Main Street Lewiston, ME 04240		24
Chicago, University of Franklin McLean Memorial Research Hospital Chicago, IL	1-50 MeV Linac	22
Columbus Hospital Great Falls, MT		28

Facility and Location	Number and Type (First Beam)	Reference
Combustion Engineering, Inc.	1-15 MeV Linac	32
911 West Main St.	2-7.5 MeV Linacs	32
Chattanooga, TN	1-4 MeV Linac	32
Confederate Memorial Medical		
Center (UC)		21
1541 Kings Highway		
Shreveport, LA 71105		
Cornell University	1-150 MeV Linac	30
10 GeV Electron Synchrotron Injector		
Ithaca, NY		
Cornell University	1-50 MeV Linac	30
2.2-GeV Electron Synchrotron Injector		
Ithaca, NY		
Cox Medical Center	1-7 MeV Linac	25
1423 N. Jefferson Street		
Springfield, MO		
Desert Samaritan Hospital	1-4 MeV Linac	15
1400 South Dobson Rd.		
Mesa, AZ 85202		
Detroit Medical Center	1-20 MeV Linac	36
Harper-Grace Hospital	1-12 MeV Linac	36
Detroit, MI	1-4 MeV Linac	36
Duhe, Henry M., M.D.		21
3024 Gentilly Blvd.		
New Orleans, LA 70122		
E. I. DuPont de Nemours & Co., Inc.	3-150 keV Linacs	
Highway 67	(1976, 1978, 1980)	57
Clinton, IA 52732	1-300 keV Linac (1974)	57
	1-175 keV Linac (1980)	57
Eastern Maine Medical Center		24
489 State Street		
Bangor, ME 04401		
Elliot Hospital	1-4 MeV Linac (1978)	53
Auburn St.	1-10 MeV Linac (1980)	53
Manchester, NH		
Ellis Fischel State Cancer Hospital	1-45 MeV Linac	25
Highway 40 and Garth Avenue		
Columbia, MO		
El Paso Cancer Treatment Center	1-18 MeV Linac	44
1901 Grandview Ave.		
El Paso, TX		

Facility and Location	Number and Type (First Beam)	Reference
Emanuel Hospital 2801 N.E. Gantenbein Portland, OR 97227		16
Emory University Clinic 1365 Clifton Rd. Atlanta, GA	1-18 MeV Linac	31
Enoch Calloway Cancer Clinic Medical DRive Atlanta, GA	1-4 MeV Linac 1-18 MeV Linac	31 31
Entel, Irwin L., M.D. Dunedin, FL	1-4 MeV Linac	10
Entel, Irwin L., M.D. New Port Richey, FL	1-6 MeV Linac	10
ESCO Corporation 2141 N.W. 25th Portland, OR 97210		16
Ethicon, Inc. Somerville, NJ		5
Evans, John C., M.D. 9100 North Central Ave. Phoenix, AZ	1-4 MeV Linac 1-Superficial Unit	15 15
Evergreen Radiology Associates 900 Sheridan Road Bremerton, WA		26
Finley Hospital 350 N. Grandview Ave. Dubuque, IA 52001	1-4 MeV Linac (1975)	57
Florida Hospital Orlando, FL	1-4 MeV Linac 1-6 MeV Linac	10 10
Florida Medical Center Lauderdale Lakes, FL	1-4 MeV Linac 1-6 MeV Linac 1-18 MeV Linac	10 10 10
Florida, University of Medical Center Gainesville, FL	1-20 MeV Linac	10
Flower Hospital 5200 Harroun Rd. Sylvania, OH	1-6 MeV e-Linac 1-20 MeV e-Linac	43 43

Facility and Location	Number and Type (First Beam)	Reference
FMC Corp. 48th-Marshall St. N. Columbia Heights, MN 55421	1-25 MeV Linac	54
Fort Sanders Presbyterian Hospital 1909 Clinch Avenue, SW Knoxville, TN	1-4 MeV Linac 1-20 MeV Linac	32 32
Georgia Baptist Hospital 315 Boulevard Atlanta, GA	1-4 MeV Linac 1-18 MeV Linac	31 31
Good Samaritan Hospital Dept. of Radiation Oncology 1033 East McDowell Rd. Phoenix, AZ 85006	1-18 MeV Linac 1-4 MeV LInac 1-Superficial Unit	15 15 15
Good Samaritan Hospital West Palm Beach, FL	3-4 MeV Linacs	10
Goodyear Tire and Rubber Co. Union City Plant Union City, TN	2-750 keV e-Linac	32
Grady Memorial Hospital 80 Butler St. Atlanta, GA	1-4 MeV LInac	31
Greenville Memorial Cancer Treatment Center Greenville, SC	1-18 MeV Linac	34
Group Health Cooperation of Puget Sound 200 15th Avenue East Seattle, WA		26
Gulf General Atomics Division of General Dynamics 100 MeV Electron Linac San Diego, CA	1-100 MeV e-Linac (1958)	5,22
Gulf South Radiation Therapy Tampa, FL	2-4 MeV Linacs	10
Gulf South Radiation Therapy LArgo, FL	1-4 MeV Linac	10
Gulf South Radiation Therapy Center 2800 Napoleon Avenue New Orleans, LA 70115		21
Gundersen Clinic La Crosse, WI	1-4 MeV Linac	52

Facility and Location	Number and Type (First Beam)	Reference
Halifax Hospital Daytona Beach, FL	1-6 MeV Linac	10
Harvard University Cambridge Electron Accelerator Cambridge, MA (*dismantled in 1973)	1-160 MeV e-Linac (1962)	1,3,5,22
Henry Ford Hospital 2799 West Grand Blvd. Detroit, MI	1-12 MeV Linac	35
Hercules, Inc. Lake Charles, LA 70669		21
Holmes Regional Medical Center Melbourne, FL	1-4 MeV Linac	10
Holston Valley Community Hospital Ravine St. Kingsport, TN	1-6 MeV LInac	32
Holt-Krock Clinic 1500 Dodson Avenue Fort Smith, AR		6
Holy Cross Hospital Ft. Lauderdale, FL	2-4 MeV Linacs	10
Honeywell, Inc. Minneapolis, MN 55408	1-300 keV Linac 1-400 keV LInac	54 54
Houma Medical & Surgical Clinic 855 Belanger St. Houma, LA 70360		21
Howard Memorial Hospital 1550 Lafayette St. Biloxi, MS 39533	1-4 MeV Electron Linac	8
Illinois, University of Urbana, IL	1-30 MeV e-Linac (1970)	22
Immanuel Medical Center 6901 North 72nd St. Omaha, NE 68122	1-6 MeV Linac	19
Institute of Radiotherapy 178-Carr. 21 Las Lomas, San Juan, PR	1-6 MeV Linac	33
Iowa Methodist Hospital 1200 Pleasant Street Des Moines, IA 50308	1-4 MeV Linac (1971)	57

Facility and Location	Number and Type (First Beam)	Reference
Jackson Memorial Hospital Miami, FL	2-4 MeV Linacs 1-13 MeV Linac	10
Jewish Hospital of Cincinnati 3200 Burnet Ave. Cincinnati, OH	1-4 MeV Linac	43
Johnson Wax Racine, WI	1-Linac	52
Kansas University Medical Center Dept. of Radiation Therapy 39th and Rainbow Kansas City, KS	1-40 MeV Linac 1-20 MeV LInac	40 40
Katzen, Melvyn J., M.D. Punta Gorda, FL	1-6 MeV Linac	10
Kentucky, University of Medical Center Room C-35 Lexington, KY	1-18 MeV Linac	12
LDS Hospital Salt Lake City, UT	1-12 MeV Linac	29
Lea Regional Hospital Box 3000 Hobbs, NM 88240		7
Lincoln General Hospital Radiation Therapy Department 2300 South 16th St. Lincoln, NE 68502	1-8 MeV Linac	19
Los Alamos Scientific Laboratory Electron Prototype Accelerator (EPA) Los Alamos, NM (*shut down in 1970)		22
Los Alamos Scientific Laboratory Los Alamos Meson Physics Facility Los Alamos, NM	1-800 MeV Proton Linac (1972)	1,22,30
Louisiana State University (2 units) Nuclear Science Center Baton Rouge, LA (*both units inactive)		41
Louisville, University of Radiation Center 500 S. Floyd Louisville, KY	1-4 MeV Linac 1-18 MeV Linac	12 12

Facility and Location	Number and Type (First Beam)	Reference
Maine Medical Center 22 Bramhall Street Portland, ME 04102		24
Manatee Memorial Hospital Bradenton, FL	1-4 MeV Linac	10
Mary Hitchcock Hospital Hanover, NH	1-4 MeV Linac (1977)	53
Maryvale Samaritan Hospital 5102 West Campbell Phoenix, AZ 85031	1-4 MeV Linac	15
Massachusetts General Hospital Boston, MA	1-35 MeV Linac (1975)	48
Massachusetts Institute of Technology Laboratory for Nuclear Science Cambridge, MA *(17 MeV unit dismantled in 1968)	1-17 MeV e-Linac 1-400 MeV e-Linac	5,22,48 22
Mayo Clinic and Foundation Rochester, MN 55901	2-4 MeV Linacs 1-18 MeV Linac	54 54
McLeod Regional Medical Center 555 E. Cheves St. Florence, SC	1-10 MeV Linac	34
McNeese State University Chemistry Dept. Lake Charles, LA 70601	1-14 MeV Linac	42
Mease Hospital Dunedin, FL	1-4 MeV Linac 1-18 MeV Linac	10
Medical Center Hospital of Vermont Colchester Avenue Burlington, VT	1-6 MeV e-Linac (1978)	23
Medical College of Central Georgia 777 Hemlock St. Macon, GA	1-4 MeV Linac	31
Medical X-Ray Center, P.C. 1417 S. Minnesota Sioux Falls, SD 57105	1-6 MeV Linac (1979)	49
Memorial Hospital 1201 South 7th Avenue Phoenix, AZ	1-4 MeV Linac	15
Memorial Hospital Hollywood, FL	1-4 MeV Linac 1-18 MeV Linac	10 10

Facility and Location	Number and Type (First Beam)	Reference
Memorial Hospital of Netrona County 1233 E. 2nd Street Casper, WY		9
Memphis Hospitals, City of 865 Jefferson Ave. Memphis, TN	1-6 MeV Linac	32
	1-18 MeV Linac	32
Mercy Hospital 301 N. Jefferson Davis Pkwy. New Orleans, LA 70119		21
Mercy Hospital Miami, FL	1-4 MeV Linac	10
Methodist Hospital Radiological Dept. 1265 Union Ave. Memphis, TN	1-6 MeV Linac	32
Methodist Hospital 6500 Excelsior Blvd. St. Louis Park, MN 55426	1-4 MeV Linac	54
Metropolitan Medical Center 900 South 8th St. Minneapolis, MN 55404	1-12 MeV Linac	54
Michael Reese Hospital Chicago, IL		5
Mid Maine Medical Center Thayer Unit North Street Waterville, ME 04901		24
Miller Duan Medical Center 504 East 2nd St. Duluth, MN 55805	1-18 MeV Linac	54
Milwaukee County Institutions Milwaukee, WI	1-4 MeV Linac	52
	1-22 MeV Linac	52
Minnesota, University of 68 MeV Proton Linac Minneapolis, MN (*dismantled in 1968)		5,22
Minnesota, University of Dept. of Environmental Health and Safety 410 Church St., SE Minneapolis, MN 55455	1-4 MeV Linac	54
	1-13 MeV Linac	54
	1-20 MeV Linac	54

Facility and Location	Number and Type (First Beam)	Reference
Mississippi Baptist Medical Center 1225 North State Street Jackson, MS 39201	1-Electron Linac	8
Mississippi, University of University, MS 38677	1-3 MeV Electron Linac	8
Mississippi, University of Medical Center, Dept. of Radiology 2500 North State Street Jackson, MS 39216	1-4 MeV Electron Linac	8
Montana College of Mineral Science and Technology West Park Street Butte, MT		28
Montana State University Missoula, MT		5
Morton F. Plant Hospital Clearwater, FL	1-6 MeV Linac	10
Mountain State Tumor Institute 151 E. Bannock Boise, ID	1-6 MeV Linac 1-18 MeV Linac	46 46
Mt. Sinai Hospital Miami Beach, FL	1-4 MeV Linac 1-8 MeV Linac	10
Myrtle Beach Radiation Therapy Center Myrtle Beach, SC	1-4 MeV Linac	34
Naples Community Hospital Naples, FL	1-12 MeV Linac	10
NASA-Space Radiation Effects Laboratory Newport News, VA *(mothballed in 1979)	1-10 MeV Linac (1966)	22
National Accelerator Laboratory Linac Injector to 8 GeV Proton Synchrotron Weston, IL	1-200 MeV Linac (1977)	22,30
National Bureau of Standards Washington, DC	1-150 MeV e-Linac (1966)	22
Naval Postgraduate School	1-100 MeV e-Linac (1965)	22
Naval Research Laboratory	1-65 MeV e-Linac (1964)	22

Facility and Location	Number and Type (First Beam)	Reference
Nebraska Methodist Hospital 8303 Dodge St. Omaha, NE 68114	1-12 MeV Linac 1-15 MeV Linac	19 19
Nebraska, University of, Hospital 42nd & Dewey Ave. Omaha, NE 68105	1-10 MeV Linac	19
Neuropsychiatric Institute 500 Mills Avenue Fargo, ND		11
New Mexico, University of Cancer Research Treatment Center Albuquerque, NM		7
North Broward Hospital Pompano Beach, FL	1-4 MeV Linac 1-10 MeV Linac 1-16 MeV Linac	10 10 10
Northern Rockies Regional Cancer Treatment Center Poly Drive and North 28th Billings, MT		28
Northside Hospital 1000 Johnson Ferry Rd. Atlanta, GA	1-6 MeV Linac	31
Oak Ridge National Laboratory Oak Ridge Electron Linear Accelerator Building 6010 Oak Ridge, TN	1-140 MeV e-Linac (1969)	22
Ocala Radiation Therapy Center Ocala, FL	1-4 MeV Linac	10
Ochsner Foundation Hospital 1516 Jefferson Hwy. New Orleans, LA 70121		21
Ohio Valley Medical Center Wheeling, WV	1-20 MeV Linac	14
Ohio State University Columbus, OH	1-6 MeV e-Linac	22,48
Oncological Clinic Ponce, PR	1-Linac	33
Oncologic Hospital Hato Rey, PR	1-8 MeV Linac	33

Facility and Location	Number and Type (First Beam)	Reference
Oregon, University of Eugene, OR 97403		16
Orlando Regional Medical Center Orlando, FL	2-6 MeV Linacs 1-18 MeV Linac	10 10
Park View Hospital 230 25th Ave., North Nashville, TN	1-4 MeV Linac 1-6 MeV Linac 1-20 MeV Linac	32 32 32
Peabody Testing Milwaukee, WI	1-4 MeV Linac	52
Pennsylvania, University of Phildelphia, PA		13
Perkins Radiation Therapy Center (2 units) 9042 Airline Hwy. Baton Rouge, LA 70815		21
Piedmont Hospital 1968 Peachtree St. Atlanta, GA	1-4 MeV Linac	31
Pikeville Methodist Hospital Highway 23 South Pikeville, KY	1-4 MeV Linac	12
Pittsburgh Plate Glass Corp. Oak Creek, WI	1-4 MeV Linac	52
Princeton-Pennsylvania Accelerator Princeton, NJ	(1963)	1
Providence Hospital 3200 Providence Drive Anchorage, AK	1-20 MeV Linac (1981)	51
Providence Medical Center 700 N.E. 47th Portland, OR 97213		16
Puerto Rico Nuclear Center Division of Radiotherapy Center for Energy Studies Medical Center Rio Piedras, PR	1-Linac	33
Purdue University (2 units) Lafayette, IN		5
Queen's Medical Center (2 units) 1301 Punchbowl St. Honolulu, HI 96813		18

Facility and Location	Number and Type (First Beam)	Reference
Radiation Center of Chattanooga 111 Whitehall Building 960 East THird St. Chattanooga, TN	1-4 MeV Linac	32
Radiation Oncology Associates 790 N. Main St. Providence, RI 02904	1-4 MeV Linac	20
Radiology Associates 716 Quincy St. Rapid City, SD 57701	1-4 MeV Linac (1977)	49
Radiology Clinic 917 General Mouton Lafayette, LA 70501		21
Radiotherapy Associates St. Petersburg, FL	1-6 MeV Linac	10
Rapides General Hospital Alexandria, LA 71301		21
Rensselear Polytechnic Institute Rensselear, NY	1-100 MeV e-Linac (1961) 1-100 MeV Proton Linac	22 22
Research Medical Center Meyer Blvd. at Prospect Avenue Kanasa City, MO	1-18 MeV Linac 1-5 Mev Linac	25 25
Rhode Island Hospital - Radiation Oncology 593 Eddy St. Providence, RI 02902	1-4 MeV Linac 1-6 MeV Linac 1-18 MeV Linac	20 20 20
Richland Memorial Hospital 3301 Harden St. Ext. Columbia, SC	1-18 MeV Linac 1-4 MeV Linac	34 34
Rogue Valley Memorial Hospital 2825 Barnett Road Medford, OR 97501		16
Sacred Heart General Hospital 1200 Alder Street Eugene, OR 97401		16
Sacred Heart Hospital (2 units) 101 8th Avenue, West Spokane, WA		26
Salem Hospital - General Unit 2561 Center Street, N.E. Salem, OR 97301		16

Facility and Location	Number and Type (First Beam)	Reference
Salem Hospital - Memorial Unit 665 Winter Street, S.E. Salem, OR 97301		16
Sarasota Radiation and Medical Oncology (3 units) Sarasota, FL	2-6 MeV Linacs 1-20 MeV Linac	10
St. Benedicts Hospital Ogden, UT	1-6 MeV Linac	29
St. Francis Hospital 2230 Liliha St. Honolulu, HI 96817		18
St. Francis Hospital 309 Jackson St. Monroe, LA 71201		21
St. John's Mercy Medical Center 615 S. New Ballas Road St. Louis, MO	1-1 MeV Linac	25
St. Joseph Hospital 601 North 30th St. Omaha, NE 68131	1-6 MeV Linac	19
St. Joseph Infirmary 735 Eastern Parkway Lousville, KY	1-2 MeV Linac	12
St. Joseph's Hospital Marshfield, WI	1-4 MeV Linac	52
St. Joseph's Hospital Milwaukee, WI	1-18 MeV Linac	52
St. Joseph's Hospital 350 West Thomas Road Phoenix, AZ	1-4 MeV Linac	15
St. Joseph's Hospital Tampa, FL	1-4 MeV Linac	10
St. Joseph's Hospital 1400 Walter, NE Albuquerque, NM		7
St. Joseph's HOspital 5665 Peachtree-Dunwoody Rd. Atlanta, GA	1-6 MeV Linac	31

Facility and Location	Number and Type (First Beam)	Reference
St. Joseph's Hospital 69 West Exchange St. St. Paul, MN 55102	1-12 MeV Linac	54
St. Jude Children's Hospital 332 North Lauderdale Memphis, TN	1-4 MeV Linac	32
St. Luke's Hospital Milwaukee, WI	1-4 MeV Linac	52
St. Luke's Hospital Wornall Road at 44th Street Kansas City, MO	1-4 MeV Linac	25
St. Mary's Hospital Main and Chisum Box 1938 Roswell, NM 88201		7
St. Mary's Hospital Huntington, WV	1-20 MeV Linac	14
St. Mary's Hospital Milwaukee, WI	1-4 MeV Linac 1-18 MeV Linac	52 52
St. Patrick's Hospital (UC) 524 South Ryan Street Lake Charles, LA 70601		21
St. Thomas Hospital 4230 Harding Rd. Nashville, TN	1-4 MeV Linac	32
St. Vincent Hospital and Medical Center (2 units) 9205 S.W. Barnes Rd. Portland, OR 97225		16
St. Vincent Hospital Green Bay, WI	1-18 MeV Linac	52
Schlosser, Joseph Vincent, M.D. 1521 St. Charles Avenue New Orleans, LA 70130		21
Schoitz Memorial Hospital Kimball & Ridgeway Waterloo, IA 50702	1-4 MeV Linac (1973)	57
Schumpert Memorial Hospital 915 Margaret Place Shreveport, LA 71101		21

Facility and Location	Number and Type (First Beam)	Reference
Sisters of Mercy Health Cooperative St. Joseph Unit 2101 Court Street Sioux City, IA 51104	1-12 MeV Linac (1973)	57
Sisters of Mercy Health Cooperative St. Vincent Unit 624 Jones Street Sioux City, IA 51105	1-4 MeV Linac (1972)	57
Sperry Univac-Det. Sys. Div. PO Box 3525 MSSIA 12 St. Paul, MN 55165	1-600 keV Linac	54
South Carolina, University of Medical University 80 Barre St. Charleston, SC	1-12 MeV Linac 2-4 MeV Linacs	34 34
South Fulton Hospital 1170 Cleveland Ave. East Point, GA	1-4 MeV Linac 1-18 MeV Linac	31 31
Southeast Missouri Hospital 1701 Lacey Cape Girardeau, MO	1-12 MeV Linac	25
Southern California, University of 31 MeV Proton Linac Los Angeles, CA (*dismantled in 1967)		22
Southwestern Louisiana, University of (2 units) Lafayette, LA		21
Southwestern Radiation Oncology, Ltd. 5200 East Grant Rd., Building 400 Tucson, AZ 85712	1-6 MeV Linac 1-4 MeV Linac	15
Stanford University Mark II 1.2 GeV Electron Linac Stanford, CA (*sent to Sao Paolo, Brazil in 1949)		22
Stanford University 2.0 GeV Mark III S Electron Linac Stanford, CA (*extension of Mark III)	(1953-III) (1972-IIIS)	1,22,30
Stanford University 22 GeV Linear Accelerator Linear Accelerator Center Stanford, CA	1966	1,22,30

Facility and Location	Number and Type (First Beam)	Reference
Stanford University 22 GeV LInear Accelerator Injector Linear Accelerator Center Stanford, CA	1-35 MeV Linac	30
Stanford Hospital San Francisco, CA		5
Stanford University (3 units) Stanford, CA		5
Stanford University Microwave Laboratory Stanford CA		5
Swedish Hospital Medical Center (2 units) Tumor Institute 1221 Madison Street Seattle, WA		26
Swedish Hospital Medical Center (2 units) 747 Summit Avenue Seattle, WA		26
Tacoma Radiation Center 314 South 'K' Street Room 11 Tacoma, WA		26
Tallahassee Memorial Hospital Tallahassee, FL	1-18 MeV Linac	10
Tennessee, University of Memorial Research Center & Hospital 1924 Alcoa Highway Knoxville, TN	1-4 MeV Linac	32
Texas, University of, at Austin 2617 Speedway, #104 Austin, TX	1-12 MeV Linac	44
Thiokol Corporation Brigham City, UT	1-15 MeV Linac	29
	1-13 MeV Linac	29
	2-10 MeV Linacs	29
	1-8 MeV Linac	29
	1-4 MeV Linac	29
Tri-City Radiology Inc. (2 units) 807 S. Auburn St. Kennewick, WA		26

Facility and Location	Number and Type (First Beam)	Reference
Trinity Lutheran Hospital 31st and Wyandotte Kansas City, MO		25
U. S. Air Force Hill Air Force Base Hill Field, UT	1-15 MeV Linac 1-10 MeV Linac 1-23 MeV Linac	29 29 29
U. S. Army Ionizing Radiation Center Lathrop, CA		5
U. S. Army Natick Labs Natick, MA	1-10 MeV Linac	48
Union Medical Center 700 West Grove Street El Dorado, AR		6
United Hospital 1200 S. Columbia Rd. Grand Forks, ND		11
Universal Propulsion Co. 1800 West Deer Valley Rd. Phoenix, AZ 85027	1-2 MeV Linac	15
University Community Hospital Tamarac, FL	1-4 MeV Linac	10
University Hospitals Madison, WI	2-4 MeV Linacs 1-18 MeV Linac	52 52
Utah, University of Salt Lake City, UT	1-8 Mev Traveling Wave Accelerator 1-4 MeV Linac 1-6 MeV Linac 1-10 MeV Linac	29 29 29 29
Utah Valley Hospital Provo, UT	1-6 MeV Linac	29
Vancouver Memorial Hospital 3400 Main Street Vancouver, WA		26
Vanderbilt University Nashville, TN	1-6 MeV Linac 1-18 MeV Linac	32 32
Veteran's Administration Hospital East 54th St. and 48th Ave., South Minneapolis, MN 55417	1-4 MeV Linac	54
Virginia, University of Charlottesville, VA		5

Facility and Location	Number and Type (First Beam)	Reference
Washington University Medical School 660 South Euclid St. Louis, MO	1-35 MeV Linac 1-4 MeV Linac	25 25
Washington, University of (3 units) University Hospital 4725 30th N.E. Seattle, WA		26
Washington, University of (3 units) 4725 30th N.E. Seattle, WA	(Non-Human Use)	26
Washington, University of (2 units) (NPL) 4725 30th N.E. Seattle, WA		26
Washingnton University Mallinckrodt Institute of Radiology 510 South Kingshighway St. Louis, MO		25
Wayne State University Medical School Detroit, MI	2-Linac	37
Wenatchee Valley Clinic 820 N. Chelan Wenatchee, WA		26
West Bank Radiation Centre 601 24th Ave., South Minneapolis, MN 55454	2-4 MeV Linacs	54
West Florida Hospital Pensacola, FL	1-4 MeV Linac 1-18 MeV Linac	10
West Jefferson General Hospital (UC) 4500 11th Street Marrero, LA 70072		21
West Virginia, University of Morgantown, WV	1-4 MeV Linac	14
Western Electric Co. 120th and "I" St. Omaha, NE 68114	1-0.4 MeV Linac	19
Western Electric (2 units) Positive Ion Accelerator Reading, PA		13

Facility and Location	Number and Type (First Beam)	Reference
Western Montana Regional Cancer Center 352 Owen Street Missoula, MT		28
Westinghouse Electric (3 units) Positive Ion Accelerator Churchill, PA		13
Whitman College Physics Dept. Walla Walla, WA		26
Willis-Knighton Memorial Hospital 2600 Greenwood Road Shreveport, LA 71103		21
Wilmington Medical Center Dept. of Radiation Therapy Wilmington, DE 19899	1-4 MeV Linac	58
Winter Haven Hospital Winter Haven, FL	1-6 MeV Linac	10
Wisconsin, University of Madison, WI	1-2 MeV Linac	52
Wyoming, University of Laramie, WY		9
Yale University New Haven, CT (*heavy ion linear accelerator dismantled in 1974)	1-HILAC (1954) 1-Linac	5,22

Synchrotrons

Facility and Location	First Beam	Reference
Argonne National Laboratory Intense Pulsed Neutron Source 0.5 GeV Proton Synchrotron Argonne, IL	1976	22
Argonne National Laboratory 12.7 GeV Proton Synchrotron (Zero Gradient Synchrotron) Argonne, IL *(decommissioning scheduled in 1979)	1963	1,22,30
Argonne National Laboratory 0.2 GeV ZGS Booster Synchrotron I Argonne, IL		30
Brookhaven National Laboratory 30 Ft. Synchrotron Upton, NY		5
Brookhaven National Laboratory 33 GeV Proton Synchrotron (Alternate Gradient Synchrotron) Upton, NY	1960	1,5,22,30
California Institute of Technology 1.1 GeV Electron Synchrotron Pasadena, CA *(dismantled in 1968)	1952	1,5,22
California, University of Medical Center San Francisco, CA		5
California, University of (2 units) Radiation Laboratory Berkeley, CA *(340 MeV Electron Synchrotron sent to Smithsonian in 1960)		5,22
California, University of 6.2 GeV Proton Synchrotron (Bevatron) Lawrence Radiation Laboratory Berkeley, CA	1954	1,5,22,30
Cornell University Electron Synchrotron Laboratory of Nuclear Studies Ithaca, NY *(dismantled)		5,22

Facility and Location	First Beam	Reference
Cornell University 10-GeV Electron Synchrotron Ithaca, NY	1967	1,30
Cornell University 2.0 GeV Electron Synchrotron Ithaca, NY *(transferred to ZGS at Argonne National Laboratory for use as booster)	1964	1,22,30
General Electric Company Schenectady, NY		5
Iowa State University (2 units) 70 MeV Electron Synchrotrons Ames, IA *(either or both 70 MeV units mothballed in 1970)	1949 1954	5,22
Massachusetts Institute of Technology 300 MeV Electron Synchrotron Cambridge, MA *(dismantled in 1960)		5,22
Michigan, University of 100 MeV Electron Synchrotron Ann Arbor, MI *(dismantled in 1960)		5,22
Midwestern Universities Research Association (3 units) Madison, WI		5
National Accelerator Laboratory Fermi Booster 8 GeV Proton Synchrotron Weston, IL	1972	1,22
National Accelerator Laboratory Fermi Main Ring 4000 GeV Proton Synchrotron Weston, IL (The 8 GEV Booster acts as the injector for this synchrotron)	1972	1,22,30
Oklahoma, University of 70 MeV Electron Synchrotron Norman, OK	1968	22
Princeton University 3 GeV Proton Synchrotron (PPA) Princeton, NJ *(sent to Argonne National Laboratory)		22

Facility and Location	First Beam	Reference
Purdue University 300 MeV Electron Synchrotron Lafayette, IN *(dismantled in 1961)		5,22
Rochester, University of 240 MeV Electron Synchrotron Rochester, NY *(stored in 1968)		22
U. S. Naval Research Laboratory Washington, D.C.		5
Virginia, University of 70 MeV Electron Synchrotron Charlottesville, VA *(put in storage in 1968)		5,22,48

Cyclotrons

Facility and Location	First Beam	Reference
M.D. Anderson Hospital and Tumor Clinic 40 MeV Cyclotron Texas Medical Center Houston, TX	1981	44
Argonne National Laboratory 60-Inch FF Cyclotron Argonne, IL	1952	2,3,5,22,27
Argonne National Laboratory Midwest Tandem Cyclotron Argonne, IL	1975	2
Brookhaven National Laboratory 60-Inch AVF Cyclotron Upton, NY	1968	2,3,22,27
Brookhaven National Laboratory 18-Inch FF Cyclotron Upton, NY (*dismantled in 1963)		22
Brookhaven National Laboratory Cosmotron Upton, NY (*dismantled in 1966)	1952	1,5,22
California, University of Center for Health Sciences Biomedical Cyclotron CS-22 Los Angeles, CA	1971	3,22,27
California, University of Radiation Laboratory 20-Inch AVF Cyclotron Livermore, CA	1969	22
California, University of 37-Inch FF Cyclotron Lawrence Radiation Laboratory Berkeley, CA (*sent to Lawrence museum in 1940)		22
California, University of 27-Inch FF Cyclotron Lawrence Radiation Laboratory Berkeley, CA (*sent to museum)		22

Facility and Location	First Beam	Reference
California, University of 50-Inch AVF Cyclotron Los Angeles, CA (*dismantled in 1973)	1962	2,22
California, University of 76-Inch AVF Cyclotron Crocker Nuclear Laboratory Davis, CA	1965	2,3,22
California, University of Lawrence Radiation Laboratory Omnitron, 88-Inch AVF Cyclotron Berkeley, CA	1962	1,22
California, University of 90-Inch FF Cyclotron Radiation Laboratory Livermore, CA (*dismantled in 1971)		5,22
California, University of Radiation Laboratory Berkeley, CA		5
Carnegie Institute of Washington 60-Inch FF Cyclotron Washington, DC (*stored in 1955)		5,22
Central High School Philadelphia, PA		13
Chicago, University of Franklin McLean Memorial Research Hospital FMI Cyclotron CS 15 950 E. 59th St. Chicago, IL		3,22
Chicago, University of 32-Inch FF Cyclotron Chicago, IL (*dismantled in 1944)		22
Chicago, University of Cancer Research Hospital Chicago, IL		22
Colorado, University of 52-Inch AVF Cyclotron Boulder, CO	1962	2,3,22

Facility and Location	First Beam	Reference
Columbia University Nevis Cyclotron Laboratories 37-Inch FF Cyclotron Irvington-on-Hudson, NY (*dismantled in 1965)		5,22
Columbia University Pupin Cyclotron Laboratory New York, NY		5
Connecticut, University of 28-Inch AVF Cyclotron Storrs, CT	1967	22,48
The Cyclotron Corp. Model CV-22 Variable Energy Compact Cyclotron Berkeley, CA	1970	2
The Cyclotron Corp. Medi-Physics Cyclotron CS-22 900 Durham Ave. South Plainfield, NJ	1973	3
Duke University 31-Inch AVF Cyclotron Durham, NC	1968	22
Georgetown University 2 cyclotrons Washington, D.C.		48
Harvard University Cyclotron Laboratory Cambridge, MA		5
Illinois, University of 50-Inch FF Cyclotron Urbana, IL (*dismantled in 1968)		5,22
Indiana University 45-Inch FF Cyclotron Bloomington, IN (*dismantled in 1968)		5,22
Indiana University Cyclotron Facility 260-Inch AVF Cyclotron Milo B. Simpson Lane Bloomington, IN	1975	3,22
Indiana University Separated Magnet-Isochronous Cyclotron Bloomington, IN	1972	2

Facility and Location	First Beam	Reference
Iowa, University of Medical Center Iowa City, IA		57
Lawrence Berkeley Laboratory 88-Inch Cyclotron 1 Cyclotron Rd. Berkeley, CA	1962	2,3
Lawrence Livermore Laboratory Injector Cyclotron Livermore, CA	1969	2,3
Los Alamos Scientific Laboratory FF Cyclotron Los Alamos, NM (*dismantled in 1974)		5,22
Mallinckrodt, Inc. (2 units) 27 MeV and 42 MeV Cyclotrons 675 Brown Road Hazelwood, MO		25
Mallinckrodt Institute of Radiology 54-Inch Cyclotron St. Louis, MO	1965	22
Maryland, University of 105-Inch Sectored Isochronous Cyclotron Department of Physics College Park, MD	1969	2,3,22
Massachusetts General Hospital Allis Chalmers Cyclotron Boston, MA		22,48
Massachusetts Institute of Technology 42-Inch FF Cyclotron Laboratory for Nuclear Science Cambridge, MA (*mothballed in 1973)		5,22,48
Medi-Physics Corp. (2 units) CS 22 Cyclotrons 5855 Christie Ave. Emeryville, CA	1970	3,22,27,45
Michigan State University K-500 Cyclotron Laboratory 500 MeV Cyclotron East Lansing, MI	1981	3,35
Michigan State University 50-MeV Cyclotron 67-Inch AVF Cyclotron East Lansing, MI *(decommissioned in 1979)	1965	2,3,22,35

Facility and Location	First Beam	Reference
Michigan, University of 83-Inch AVF Cyclotron Ann Arbor, MI (*dismantled in 1978)		2,22
Michigan, University of 50-Inch FF Cyclotron Ann Arbor, MI (*mothballed in 1970)	1936	5,22
Mt. Sinai Medical Center Anna & Louis Hand Cyclotron Complex, Model CS-30 4300 Alton Rd. Miami Beach, FL	1972	3,10,22
NASA-Lewis Research Center 60-Inch FF Cyclotron 21000 Brookpark Rd. Cleveland, OH	1952	3,5,22,27
New England Nuclear Corp. 601 Treble Cove Rd. N. Billerica, MA		
Cyclotron #1 (CS-22)	1970	2,3,22,27
Cyclotron #2 (CS-30)	1976	3,22,27
Cyclotron #3	1978	3
Cyclotron #4	1980	3
Naval Radiation Defense Laboratory (NRDL) NRDL Cyclotron San Francisco, CA (*NRDL was disestablished 11/3/69)	1967	2
Oak Ridge National Laboratory Accelerator for Physics & Chemistry of Heavy Elements Oak Ridge, TN	1975	2
Oak Ridge National Laboratory (4 units) Oak Ridge, TN (*a 63-Inch FF unit was sent to museum in 1962)		5,22
Oak Ridge National Laboratory Hollifield Heavy Ion Research Facility, Building 6000 Oak Ridge (76-Inch AVF) Isochronous Cyclotron Oak Ridge, TN	1964	2,3,22,27
Ohio State University 45-Inch FF Cyclotron Columbus, OH (*shut down in 1972)		22,48

Facility and Location	First Beam	Reference
Oregon State University 37-Inch AVF Cyclotron Corvallis, OR (*dismantled in 1973)	1969	2,22
Pittsburgh University 45-Inch FF Cyclotron Radiation Laboratory Pittsburgh, PA (*dismantled in 1967)		5,22
Princeton University Joseph Henry Laboratory of Physics 69-Inch AVF Cyclotron Princeton, NJ	1968	2,3,22
Purdue University 37-Inch FF Cyclotron Lafayette, IN (*dismantled in 1968)		5,22
Rochester University (2 units) Rochester, NY		5
St. Louis University 27-Inch FF Cyclotron St. Louis, MO	1966	22
Sloan-Kettering Institute for Cancer Research Sloan-Kettering Institute Cyclotron (CS-15) 410 E. 68th St. New York, NY	1967	2,3,22,27
Stanford University Stanford, CA		5
Texas A&M University 88-Inch AVF Cyclotron College Station, TX	1967	2,3,22,44
Triangle University Nuclear Laboratory Cyclo-Graaff Injector Duke University, NCSU & UNC-CH Durham, NC	1968	2,3
U.S. Naval Research Laboratory (4 units) Washington, DC		5
U.S. Naval Research Laboratory 76-Inch AVF Cyclotron Radiation Technology Division Washington, DC	1967	2,3,22

Facility and Location	First Beam	Reference
Washington University Sector Focused Cyclotron St. Louis, MO	1965	2,3,5,25
Washington University Medical School Cyclotron II (CS-15) Barnard Hospital St. Louis, MO	1976	3,22,25,27
Washington University Medical School 7 MeV Allis Chalmers Cyclotron 660 South Euclid St. Louis, MO		25,27
Washington, University of 60-Inch FF Cyclotron Seattle, WA	1951	3,22
Yale University Sloane Physics Laboratory New Haven, CT		5

Synchrocyclotrons

Facility and Location	First Beam	Reference
California, University of Lawrence Berkeley Laboratory 730 MeV Proton Synchrocyclotron (184-inch) Berkeley, CA	1946	3,22
California, University of 41-Inch Synchrocyclotron Los Angeles, CA *(dismantled in 1961)		22
Carnegie Mellon University 450 MeV Proton Synchrocyclotron (141-inch) Saxonburg, PA *(dismantled in 1973)		5,22
Chicago, University of Enrico Fermi Institute for Nuclear Studies 450 MeV Proton Synchrocyclotron (170-inch) Chicago, IL *(unit partially dismantled)		5,22
Columbia University 585 MeV Proton Synchrocyclotron Irvington, NY	1950	3,22
NASA-Space Radiation Effects Laboratory College of William and Mary 660 MeV Proton Synchrocycllotron (197-Inch) Newport News, VA *(mothballed in 1979)	1965	3,22
Princeton University 20 MeV Proton Synchrocyclotron (35-inch) Palmer Physical Laboratory Princeton, NJ *(mothballed in 1967)		5,22
Rochester, University of 240 MeV Proton Synchrocyclotron (130-Inch) Rochester, NY *(dismantled in 1968)	1948	5,22

Betatrons

Facility and Location	Number and Type (First Beam)	Reference
AEC, Ltd. Milwaukee, WI	1-18 MeV Betatron	55
Allis-Chalmers Milwaukee, WI	1-28 MeV Betatron 1-22 MeV Betatron	5 55
ARO, Inc. Arnold Air Force Station Tullahoma, TN	1-25 MeV Betatron 1-1 MeV Resotron	32 32
Atlanta West Hospital Atlanta, GA	1-45 MeV Betatron	31
Baldwin-Lima-Hamilton Corporation Lima, OH	1-24 MeV Betatron	5
Birdsboro Steel Foundry Birdsboro, PA	1-24 MeV Betatron	5
Bonney-Floyd Steel Castings Co. Columbus, OH	1-24 MeV Betatron	5
Broward General Hospital Ft. Lauderdale, FL	1-25 MeV Betatron	10
Case Western Reserve University Cleveland, OH	1-30 MeV Betatron	5
Chicago, University of Chicago, IL *(dismantled in 1955)	1-100 MeV Betatron	5,22
Cincinnati, University of Cincinnati, OH	1-12 MeV Betatron	48
Continental Foundry and Machine Company Coraopolis, PA	1-24 MeV Betatron	5
Continental Foundry and Machine Company East Chicago, IN	1-24 MeV Betatron	5
Cox Medical Center 1423 N. Jefferson St. Springfield, MO		25

Facility and Location	Number and Type (First Beam)	Reference
Detroit Arsenal Ordnance Corps Center Line, MI	1-15 MeV Betatron	5
Electric Steel Foundry Co. Portland, OR	1-22 MeV Betatron 1-50 MeV Betatron 1-100 MeV Betatron	5 5 5
Emory University Clinic 1365 Clifton Rd. Atlanta, GA	1-25 MeV Betatron	31
ESCO Corporation 2141 N.W. 25th Portland, OR 97210		16
General Electric Company Knolls Atomic Power Laboratory Schenectady, NY *(scrapped in 1970)	1-100 MeV Betatron	5,22
General Electric Research Lab. Schenectady, NY *(dismantled in 1973)	1-100 MeV Betatron	5,22
General Steel Castings Company Eddystone, PA	1-24 MeV Betatron	5
General Steel Castings Company Granite City, IL *(closed in 1977)	1-24 MeV Betatron	5
Henry Ford Hospital 2799 West Grand Blvd. Detroit, MI *(dismantled in 1981 with components sold to Chicago firm for scrap)	1-35 MeV Betatron (1969)	35
Hercules Corporation Magna, UT	2-25 MeV Betatron 1-16 MeV Betatron	29
Illinois, University of Urbana, IL *(300 MeV and 25 MeV units dismantled in 1968 and 1972 respectively)	1-300 MeV Betatron 1-25 MeV Betatron 1-80 MeV Betatron	5,22 5,22 5,22
Illinois, University of Medical School Chicago, IL	1-24 MeV Betatron	5

Facility and Location	Number and Type (First Beam)	Reference
Iowa, University of Medical Center Iowa City, IA		57
Los Alamos Scientific Laboratory Los Alamos, NM *(Junked in 1970)	1-15 MeV Betatron	5
Los Alamos Scientific Laboratory Los Alamos, NM *(Junked in 1955)	11-10 MeV "portable" Betatron	22
Los Alamos Scientific Laboratory Los Alamos, NM *(sent to U. of New Mexico in 1955)	1-10 MeV "portable" Modified Betatron	22
Madison Radiation Center Madison, WI	1-24 MeV Betatron	5
Memorial Center New York, NY	1-24 MeV Betatron	5
Mesta Machine Co. Homestead, PA	1-24 MeV Betatron	5
Methodist Hospital Radiology Dept. 1265 Union Ave. Memphis, TN	1-25 MeV Betatron	32
Michigan University Ann Arbor, MI	1-24 MeV Betatron	5
Milwaukee County Institutions Milwaukee, WI	1-22 MeV Betatron	55
Mt. Sinai Hospital New York, NY	1-24 MeV Betatron	5
National Bureau of Standards Washington, DC *(decommissioned in 1965)	1-50 MeV Betatron	5,22
Ohio Steel Castings Co. Lima, OH	1-24 MeV Betatron	5
Oregon Health Sciences University (Formerly U. of Oregon Health Sciences Center) 3181 S.W. Sam Jackson Road Portland, OR 97201		16

Facility and Location	Number and Type (First Beam)	Reference
Pennsylvania, University of Philadelphia, PA	1-24 MeV Betatron	5
Picatinny Arsenal Dover, NJ	1-24 MeV Betatron	5
Pittsburgh Steel Foundry Corp. Glassport, PA	1-24 MeV Betatron	5
Presbyterian Hospital New York, NY	1-25 MeV Betatron	5
Rensselaer Polytechnic Institute Troy, NY *(dismantled in 1968)	1-30 MeV Betatron	5,22
Stiennan, O.A., M.D. Madison, WI	1-28 MeV Betatron	55
Texas, University of Anderson Hospital and Tumor Institute Houston, TX	1-24 MeV Betatron	5
St. Joseph's Hospital Tampa, FL	1-4 MeV Betatron	10
U.S. Naval Ordnance Laboratory Silver Spring, MD	1-10 MeV Betatron	5
U.S. Naval Research Laboratory Washington, DC	1-21 MeV Betatron	5
U.S. Navy Electronics Laboratory San Diego, CA	1-26 MeV Betatron	5
Valley Forge Corporate 611 Marion Rd. Columbus, OH	1-24 MeV Betatron (1956)	43
Washington University School of Medicine St. Louis, MO	1-24 MeV Betatron	5,25
Watervliet Arsenal Watervliet, NY	1-24 MeV Betatron	5
Wisconsin, University of Research Facility 3725 Schneider Rd., Route 4 Stoughton, WI	1-Microtron	55

Miscellaneous

Facility and Location	Type	Reference
Advanced Micro Devices 5204 East Ben White Blvd Austin, TX 78760		44
Aerojet Liquid Rocket Co. Sacramento, CA 95813	1 accelerator $\leq$ 10 MeV	45
Aerojet Manufacturing Co. 601 S. Placentia Fullerton, CA 92631	1 accelerator $\leq$ 10 MeV 1 accelerator $\geq$ 10 MeV	45 45
Aerojet Solid Propulsion Co. Building 11 Sacramento, CA 95813	1 accelerator $\leq$ 10 MeV 1 accelerator $\geq$ 10 MeV	45 45
The Aerospace Corp. 2350 E. El Segundo Blvd. El Segundo, CA 90009	1 accelerator $\leq$ 10 MeV	45
Amdahl Corporation 1250 E. Argus Avenue Sunnyvale, CA 94086	2 accelerators $\geq$ 10 MeV	45
American Micro Systems Inc. 3800 Homestead Rd. Santa Clara, CA 95051	3 accelerators $\geq$ 10 MeV	45
Amarillo Medical Center Don & Sybil Harrington Cancer Ctr. 1500 Wallace Blvd. Amarillo, TX		44
Angelo State University 2601 West Avenue N. San Angelo, TX 76909		44
Arkansas, University of Fayetteville, AR	1-0.4 MeV High Voltage Rectifier	5
ATC Medical Technology Inc. 570 Del Rey Sunnyvale, CA	4 accelerators $\leq$ 10 MeV	45
Avantek Inc. 3175 Bowers Ave. Santa Clara, CA 95051	2 accelerators $\geq$ 10 MeV	45
Baylor University Department of Chemistry Waco, TX	1-2 MeV accelerator	44

Facility and Location	Type	Reference
Baylor University Medical Center Charles A. Sammons Cancer Center 3500 Gaston Avenue Dallas, TX		44
Bethesda Hospital (UC) 10500 Montgomery Rd. Cincinnati, OH	1 accelerator	43
California, University of at Los Angeles Health Sciences Dept. 405 Hilgard Los Angeles, CA	1-Health Science Dept. unit 1-Env. Health & Safety unit	45 45
California, University of at San Francisco Moffitt Hospital Paranassas Avenue San Francisco, CA 94117	1-Radiation Therapy unit	45
Case Western Reserve University 202 Quail 10900 Euclid Ave. Cleveland, OH	3 accelerators	43
Cedars-Sinai Medical Center 8700 Beverly Blvd. Los Angeles, CA	1-Radiation Therapy unit	45
Chevron Research Co. 576 Standard Ave. Richmond, CA 94804	1 accelerator ≥ 10 MeV	45
University of Cincinnati Hospital 234 Goodman Cincinnati, OH	1 accelerator	43
City of Hope Medical Center 1500 E. Duarte Road Duarte, CA 91010	1-Radiation Therapy unit	45
Cleveland Clinic Foundation 9500 Euclid Ave. Cleveland, OH	1 accelerator	43
Crown Zellerbach Corp. 2199 Williams St. San Leandro, CA 94577	1 accelerator ≤ 10 MeV	45
The Cyclotron Corp. 950 Gilman St. Berkeley, CA 94710	1 accelerator ≤ 10 MeV 3 accelerators ≥ 10 MeV	45 45

Facility and Location	Type	Reference
Data General Corp. 433 N. Mathilda Ave. Sunnyvale, CA 94086	1 accelerator ≤ 10 MeV 2 accelerators ≥ 10 MeV	45 45
Del Rio High School 100 Memorial Drive Del Rio, TX 78840		44
Eaton Corporation PCC Division 1199 South Chillicothe Rd. Aurora, OH	3 accelerators	43
Economy Foods, Inc. 961 Charleston Rd. Palo Alto, CA 94303	1 accelerator ≥ 10 MeV	45
EG&G Inc. 130 Robin Hill Rd. Goleta, CA 93017	1 accelerator ≥ 10 MeV	45
EG&G Inc. 820 Francis Botello Goleta, CA 93017	1 accelerator ≥ 10 MeV	45
Electronic Arrays Inc. 501 Ellis St. 550 Middlefield Rd. Mountain View, CA 94043	2 accelerators ≤ 10 MeV	45
Essex Group Power Conductor 3400 East Union Street Lafayette, IN 47903	1-0.4 MeV unit 1-1.5 MeV unit (1975)	56
Exxon Corp., USA Baytown, TX		44
Fairchild-Exetron Division 3105 Alfred St. Santa Clara, CA 95050	2 accelerators ≤ 10 MeV	45
Fairchild Semiconductor R&D Laboratory 4001 Miranda Ave. Palo Alto, CA 94304	3 accelerators ≤ 10 MeV	45
Fairchild Semiconductor Diode 4300 Redwood Highway San Rafael, CA 94903	1 accelerator ≤ 10 MeV	45
Firestone Tire and Rubber Co. Plant 2 1200 Firestone Parkway Akron, OH	1 accelerator	43

Facility and Location	Type	Reference
Firestone Tire and Rubber Co. Central Research Laboratory 1200 Firestone Parkway Akron, OH	2 accelerators	43
Daniel Freeman Hospital 333 N. Prarie Inglewood, CA	Radiation Therapy unit	45
Frontier Inc. 2955 N. Airway Ave. Costa Mesa, CA 92626	2 accelerators $\leq$ 10 MeV	45
Goodyear Tire and Rubber Co. 1144 East Market St. Akron, OH	2 accelerators	43
GCA Corp. 1050 Kifer Rd. Sunnyvale, CA 94086	1 accelerators $\geq$ 10 MeV	45
General Atomic Co. 10955 John J. Hopkins San Diego, CA 92121	1 accelerator $\geq$ 10 MeV	45
General Dynamics-Pomona 1675 West Mission Blvd. Pomona, CA 91766	1 accelerator $\geq$ 10 MeV	45
Hewlett-Packard 10900 Wolfe Rd. Cupertino, CA 95014	1 accelerator $\leq$ 10 MeV 3 accelerators $\geq$ 10 MeV	45 45
Hewlett-Packard 1501 Page Mill Rd. Palo Alto, CA 94304	3 accelerators $\geq$ 10 MeV	45
Hewlett-Packard 3500 Deer Creek Rd. Palo Alto, CA 94304	1 accelerator $\geq$ 10 MeV	45
Hewlett-Packard 350 W. Trimble Rd. San Jose, CA 95131	1 accelerator $\geq$ 10 MeV	45
Hewlett-Packard 1400 Fountain Dr. Pkwy. Santa Rosa, CA 95404	2 accelerators $\leq$ 10 MeV	45
Houg Memorial Presbyterian Hospital 301 Newport Blvd. Newport Beach, CA	Radiation Therapy unit	45

Facility and Location	Type	Reference
Houston, University of 3801 Cullen Blvd. Houston, TX	1-1.2 MeV accelerator	44
Hughes Aircraft 500 Superior Ave. Newport Beach, CA 92663	4 accelerators $\geq$ 10 MeV	45
IBM Corp. 5600 Cottle Rd. San Jose, CA 95193	1 accelerator $\geq$ 10 MeV	45
Information Magnetics Corp. 460 Ward Drive Goleta, CA 93017	1 accelerator $\geq$ 10 MeV	45
Indiana University 625 N. Jordan Bloomington, IN 47405	1-0.2 MeV unit (1975)	56
Intercommunity Hospital/Covina 303 N. Third Avenue Covina, CA 91723	1-Radiation Therapy unit	45
Intersil Inc. 10900 N. Tantau Cupertino, CA 95014	2 accelerators $\geq$ 10 MeV	45
Intersil Inc. 1276 Hammerwood Sunnyvale, CA 95014	1 accelerator $\geq$ 10 MeV	45
Intersil Inc. 3250 Scott Blvd. Santa Clara, CA 95051	2 accelerators $\geq$ 10 MeV	45
Intel Corporation 3065 Bowers Ave. Santa Clara, CA 95051	2 accelerators $\geq$ 10 MeV	45
Ilco Inc. 3350 Scott Blvd., #5902 Santa Clara, CA 95051	1 accelerator $\leq$ 10 MeV	45
IRT 10955 J.J. Hopkins Drive San Diego, CA 92121	2 accelerators $\geq$ 10 MeV	45
Kettering Medical Center 3535 Southern Blvd. Kettering, OH	1 accelerator	43
Lockheed Missiles & Space Co. 1111 Lockheed Way Sunnyvale, CA 94088	1 accelerator $\leq$ 10 MeV	45

Facility and Location	Type	Reference
Lockheed Aircraft Corp. Missiles Division Facility 2 3251 Hanover St. Palo Alto, CA 94304	2 accelerators $\leq$ 10 MeV	45
Maxwell Laboratories, Inc. 9244 Balboa Ave. San Diego, CA 92123	4 accelerators $\leq$ 10 MeV	45
Medical College of Ohio (Hospital/School) 3000 Arlington Ave. C.S. 10008 Toledo, OH	1 accelerator	43
Monolithic Memories Inc. 1165 E. Argus Ave. Sunnyvale, CA 94086	1 accelerator $\geq$ 10 MeV	45
Granville C. Morton Cancer Research Hospital 9000 Harry Hines Blvd. Dallas, TX 75235		44
Mt. Carmel Medical Center 793 West State Street Columbus, OH	1 accelerator	43
National Bureau of Standards Washington,DC	1-A. C. Rectifier	5
National Semiconductor 2900 Semiconductor Dr. Santa Clara, CA 95051	11 accelerators $\leq$ 10 MeV	45
NL Industries, Inc. McCulloch Services Dept. Barold Division 405 McCarty Houston, TX		44
Notre Dame, University of South Bend, IN	1-0.5 MeV unit (1980)	56
Oak Ridge National Laboratory Oak Ride, TN	1-0.6 MeV Cascade	5
Ohio State University Dept. of Chemistry 88 W. 18th Avenue Columbus, OH	2 accelerators	43

Facility and Location	Type	Reference
Ohio State University Hospitals 410 W. 10th Avenue Columbus, OH	2 accelerators	43
Ohio University Hudson Health Center Athens, OH	2 accelerators	43
Ohio Valley Medical Center Wheeling, WV	1-X-Ray Therapy Machine	14
Pacific Southern Foundries Inc. 600 21st Street Bakersfield, CA 93301	1 accelerator ≤ 10 MeV	45
Palo Alto Medical Center 300 Horner Avenue Palo Alto, CA 94301	1-Radiation Therapy unit	45
Peninsula Hospital & Medical Ctr. 1783 El Camino Real Burlingame, CA 94010	1-Radiation Therapy unit	45
Precision Monolithics Inc. 1500 Space Park Drive Santa Clare, CA 95050	1 accelerator ≥ 10 MeV	45
Purdue University West Lafayette, IN 47907	1-0.2 MeV unit (1980)	56
Radiation Center 1425 Enderly Place E. Ft. Worth, TX 76104		44
Radiology Nuclear Medical Group 611 Airport Drive Bakersfield, CA 93308	1-Radiation Therapy unit	45
Raychem Corporation 300 Constitution Dr. Menlo Park, CA 94025	6 accelerators ≤ 10 MeV	45
Raychem Corporation Oakside at Northside Redwood City, CA 94064	2 accelerators ≥ 10 MeV	45
Raytheon Co. 350 Ellis Street Mountain View, CA 94041	1 accelerator ≥ 10 MeV	45
Redwood Radiology Associates 121 Stoyome Street Santa Rosa, CA	1-Radiation Therapy unit	45

Facility and Location	Type	Reference
Rice University Materials Science Dept. Houston, TX	1-1 MeV accelerator	44
RIS Irrigation Systems 1588 N. Marshall Avenue El Cajon, CA 92020	1 accelerator ≤ 10 MeV	45
Riverside Methodist Hospital 3535 Olentangy River Road Columbus, OH	1 accelerator	43
Rockwell International Collins Radio Division 4311 Jamboree Road Newport Beach, CA	5 accelerators ≥ 10 MeV	45
Rockwell International Science Center 1049 Camino Dos Rios Thousand Oaks, CA 91360	3 accelerators ≥ 10 MeV	45
St. Joseph Medical Center Buena Vista & Alameda Burbank, CA 91505	1-Radiation Therapy unit	45
St. Vincent Charity Hospital Dept. of Radiology 2351 East 22nd Street Cleveland, OH	1 accelerator	43
Santa Ana-Tustin Community Hospital 1001 N. Tustin Avenue Santa Ana, CA	1-Radiation Therapy unit	45
Siliconix Inc. 2201 Laurelwood Rd. Santa Clara, CA 95054	2 accelerators ≥ 10 MeV	45
Solitron Devices Inc. 8808 Balboa Ave. San Diego, CA 92123	1 accelerator ≥ 10 MeV	45
South Bay Hospital 514 N. Prospect Redondo Beach, CA	1-Radiation Therapy unit	45
Southern California Permanente 6041 Cadillac Drive Los Angeles, CA	1-Radiation Therapy unit	45
Southern Methodist University Department of Physics Dallas, TX		44

Facility and Location	Type	Reference
Stanford Research Institute Palo Alto, CA	1-Resonant transformer	5
Stanford University Hospital 67 Encina Hall Stanford, CA 94305	1-Radiation Therapy unit	45
Sutter Memorial Hospital 52nd & F Streets Sacramento, CA	1-Radiation Therapy unit	45
Texas, University of Austin, TX	1-Full-wave, four-tube rectifier	5
Texas Tech University Lubbock, TX	1-2 MeV accelerator 1-10 MeV accelerator	44 44
Texas, University of, at Dallas Richardson, TX	1-1 MeV accelerator	44
Texas, University of Electrical Engineering Dept. Arlington, TX		44
Texas, University of SW Medical School 5323 Harry Hines Blvd. Dallas, TX		44
Texas, University of, at El Paso El Paso, TX		44
Texas, University of Medical Branch 14th & Port Industrial Blvd. Galveston, TX		44
Texas, University of Health Science Center 7703 Floyd Curl Drive San Antonio, TX		44
The Toledo Hospital 2142 North Cove Blvd. Toledo, OH	1 accelerator	43
Toledo, University of 2801 W. Bancroft Street Toledo, OH	1 accelerator	43
TRW Defense & Space Systems Group One Space Park Redondo Beach, CA 90278	4 accelerators $\leq$ 10 MeV	45

Facility and Location	Type	Reference
Varian Associates Radiation Division 611 Hansen Way, Bldg. 3 Palo Alto, CA 94303	4 accelerators $\geq$ 10 MeV	45
Vons Grocery Co. 4344 N. Shirley Avenue El Monte, CA 91731	1 accelerator $\geq$ 10 MeV	45
Vought Corp. Dallas, TX		44
Welex A Halliburton Company Houston, TX		44
Westlake High School 601 Camp Craft Road Austin, TX		44
Wright State University Col. Glenn Highway Dayton, OH	1 accelerator	43
Zilog 10460 Bubb Road Cupertino, CA 95014	3 accelerators $\geq$ 10 MeV	45

Direct Current Machines

Facility and Location	Number and Type (First Beam)	Reference
Aerospace Research Laboratory (no address)	1-2 MeV V. de Graaff (1953)	22
Argonne Cancer Research Hospital University of Chicago Chicago, IL	1-2 MeV V. de Graaff	5
Argonne National Laboratory Argonne, IL	1-2 MeV V. de Graaff 1-3 MeV V. de Graaff	5,22 5,22
Argonne National Laboratory Zero Gradient Injectors Argonne, IL	2-0.75 MeV Cockroft-Walton (1967) 1-4MeV Dynamitron (1969)	1,30 22
Arizona, University of Tucson, AZ	1-5.5 MeV V. de Graaff (1968)	22
Arkansas, University of Fayetteville, AR	1-Cockroft-Walton 1-V. de Graaff	6 6
Arkansas, University of 33rd & University Avenue Little Rock, AR	1-V. de Graaff	6
Atomics International Canoga Park, CA	1-1.6 MeV V. de Graaff	5
Auburn University Edmund C. Leach Nuclear Science Center Auburn, AL	1-3 MeV Dynamitron (1970)	47
Augusta Radiation Therapy Center University Hospital University Place Augusta, GA	1-2 MeV V. de Graaff	31
Austenal, Inc. Chicago, IL	1-1 MeV V. de Graaff	5
Babcock and Wilcox Lynchburg, VA	1-1 MeV V. de Graaff	5
Bartol Research Foundation of the Franklin Institute Swarthmore, PA	1-0.13 MeV Cockroft-Walton 1-5 MeV V. de Graaff (1952) 1-1.7 MeV V. de Graaff	5 5,13,22 5

Facility and Location	Number and Type (First Beam)	Reference
Baylor University College of Medicine Houston, TX	1-2 MeV V. de Graaff	5
Bell Telephone Labs New York, NY	2-1 MeV V. de Graaff	5
Boston College Chestnut Hill, MA	1-Van de Graaff	48
Brigham Young University Provo, UT	1-2.5 MeV V. de Graaff (1965) 1-4 MeV V. de Graaff (1970)	22,29 22,29
Brookhaven National Laboratory Upton, NY	2-4 MeV V. de Graaff 1-3 MeV Dynamitron 2-2 MeV V. de Graaff	5 22 22
Brookhaven National Laboratory Alternating Gradient Synchrotron Injector Upton, NY	1-0.78 MeV Cockroft-Walton (1960)	1,30
California Institute of Technology Pasadena, CA	1-0.6 MeV V. de Graaff 1-2.8 MeV V. de Graaff	5,22 5,22
California Research Corp. Richmond, CA	1-2 MeV V. de Graaff	5
California, University of Lawrence Radiation Laboratory Bevatron Injector Berkeley, CA	1-0.48 MeV Cockroft-Walton (1962) 1-0.75 MeV Cockroft-Walton 1-0.75 MeV Cockroft-Walton (Heavy Ion Injector)	1,30 30 30
*(0.75 MeV Cockroft-Walton injector formerly used as AGS Injector at BNL)		
California, University of Radiation Laboratory Berkeley, CA	2-0.5 MeV Cockroft-Walton 1-4 MeV V. de Graaff	5
California, University of Radiation Laboratory Livermore, CA	1-1 MeV V. de Graaff 1-0.5 MeV Cockroft-Walton	5
Carnegie Institute Washington, DC	1-4 MeV V. de Graaff (1938)	5,22
Carnegie Mellon Institute Pittsburgh, PA	1-3 MeV V. de Graaff	5
Charity Hospital of Louisiana at New Orleans 1532 Tulane Avenue New Orleans, LA 70112	1-V. de Graaff	21

Facility and Location	Number and Type (First Beam)	Reference
Case Western Reserve University Cleveland, OH	1-3 MeV V. de Graaff (1958)	22
Chicago Bridge & Iron Co. Birmingham, AL	1-1 MeV V. de Graaff 2-2 MeV V. de Graaff	5 5
Chicago Nuclear (formerly Texas Nuclear) Austin, TX *(shutdown in 1972)	1-3.2 MeV V. de Graaff (1956)	5,22
Chicago, University of Chicago, IL	1-0.45 MeV Cockroft-Walton	5
Chicago, University of Franklin McLean Research Hospital Chicago, IL	1-2 MeV V. de Graaff	22
Clemson University Clemson, SC	1-0.4 MeV V. de Graaff	34,48
Columbia University Pupin Cyclotron Laboratories New York, NY *(shut down in 1970)	1-5.5 MeV V. de Graaff (1955)	5,22
Connecticut, University of Storrs, CT	1-0.25 MeV Cockroft-Walton 1-1 MeV V. de Graaff	5 48
Cooper Alloy Corp. Hillside, NY	1-1 MeV V. de Graaff	5
Cornell University Ithaca, NY	1-2 MeV V. de Graaff	5
Delaware, University of 417 Academy St. Newark, DE 19711	1-V. de Graaff	58
Dow Chemical Co. Midland, MI	2-0.5 MeV V. de Graaff	5
Dow Chemical Co. Western Division Pittsburg, CA	1-2.5 MeV V. de Graaff	5
Duke University Durham, NC	1-4 MeV V. de Graaff	5
E.I. DuPont de Nemours, Inc. Wilmington, DE	1-2 MeV V. de Graaff 1-3 MeV V. de Graaff	5 5
Element Analysis Corp. Tallahassee, FL	1-3 MeV V. de Graaff	10

Facility and Location	Number and Type (First Beam)	Reference
Eugene Talmadge Memorial Hospital Augusta, GA	1-2 MeV V. de Graaff	5
Ethicon Inc. Somerville, NJ	1-2.5 MeV V. de Graaff	5
Evans Signal Laboratory Belmar, NJ	1-2 MeV V. de Graaff	5
Fairleigh Dickinson University Teaneck, NJ	1-V. de Graaff	48
Florida, University of Gainesville, FL *(1 MeV unit dismantled in 1965)	1-4.2 MeV V. de Graaff (1964) 1-1 MeV V. de Graaff 1-2 MeV v. de Graaff	10,22 5,22 10
Florida State University Tallahassee, FL	1-20 MeV V. de Graaff (1970) 1-4 MeV V. de Graaff 1-12 MeV V. de Graaff	10,22 10,48 48
Foster-Wheeler Corp. Mountaintop, PA	1-2 MeV V. de Graaff	5
General Electric Co. Hanford Laboratories Richland, WA	2-2 MeV V. de Graaff	5
General Electric Co. Aircraft Nuclear Propulsion Dept. Cincinnati, OH	1-2 MeV V. de Graaff	5
General Electric Valley Forge Space Center Valley Forge, PA	1-V. de Graaff	13
Georgetown University Washington, DC	1-0.4 MeV V. de Graaff (1964) 1-2 MeV V. de Graaff (1966)	22,48 22,48
Georgia Institute of Technology Dept. of Physics 225 North Avenue Atlanta, GA	1-Van de Graaff	31
Georgia Southern College Statesboro, GA	1-2 MeV V. de Graaff	31
Georgia, University of Athens, GA	1-5 MeV V. de Graaff (1970)	22,31
Arnold Greene, Inc. Cambridge, MA	1-1 MeV V. de Graaff	5

Facility and Location	Number and Type (First Beam)	Reference
Gulf Research and Development Co. Pittsburgh, PA	1-3 MeV V. de Graaff	5
Hercules Inc. 9th and Market St. Wilmington, DE 19899	1-V. de Graaff	58
Honeywell St. Petersburg, FL	1-2 MeV V. de Graaff	10
Hope College 12th St. Holland, MI	1-2.5 MeV V. de Graaff (1973)	38
Humble Oil and Refining Co. Houston, TX	1-2 MeV V. de Graaff	5
Idaho State University School of Engineering Pocatello, ID	1-0.2 MeV V. de Graaff	46
Iowa State University Ames, IA *(4 MeV unit dismantled in 1964)	1-0.5 MeV Cockroft-Walton 1-4 MeV V. de Graaff 1-0.3 MeV Cockroft-Walton	5 5,22 5
Iowa, University of Iowa City, IA	1-6 MeV V. de Graaff (1964) 1-2 MeV V. de Graaff (1961)	22 22
Johns Hopkins University Baltimore, MD *(1 MeV unit dismantled in 1962, 3 MeV unit dismantled in 1974)	1-3 MeV V. de Graaff (1963) 1-1 MeV V. de Graaff	5,22 22
Kansas, University of Lawrence, KS *(3 MeV unit sold in 1976)	1-3 MeV V. de Graaff 1-4 MeV V. de Graaff	5,40 22
Kentucky, University of Lexington, KY	1-6 MeV V. de Graaff (1964) 1-14 MeV Cockroft-Walton 1-2.2 MeV V. de Graaff 1-0.12 MeV Cockroft-Walton	12,22,48 12 5 5
Lehigh University Bethlehem, PA	1-3 MeV V. de Graaff (1976)	13,48
Lemuel Shattuck Hospital for Chronic Diseases Boston, MA	1-2 MeV V. de Graaff	5
Lockheed Aircraft Corp. Missile Systems Division Palo Alto, CA	1-3 MeV V. de Graaff (1958)	5,22

Facility and Location	Number and Type (First Beam)	Reference
Los Alamos Scientific Laboratory Los Alamos, NM *(2.5 MeV V. de Graaff units dismantled in 1963 and 1965)	1-8 MeV V. de Graaff (1950) 2-2.5 MeV V. de Graaff 1-0.50 MeV Cockroft-Walton 1-0.25 MeV Cockroft-Walton 1-3 MeV V. de Graaff (1969)	5,22 5 5 5 22
Los Angeles Tumor Clinic Los Angeles, CA	1-2 MeV V. de Graaff	5
Louisiana State University Baton Rouge, LA *(dismantled in 1966)	1-1 MeV V. de Graaff	22
Lowell Tech. Institute Lowell, MA	1-6 MeV V. de Graaff (1969)	22
Magnolia Petroleum Co. Dallas, TX	1-0.5 MeV V. de Graaff 1-2 MeV V. de Graaff	5 5
Maryland, University of College Park, MD	1-3.5 MeV V. de Graaff (1958)	22
Massachusetts General Hospital Boston, MA	1-2.0 MeV V. de Graaff	5
Massachusetts, University of Amherst, MA	1-0.5 MeV V. de Graaff	48
Massachusetts Institute of Technology Laboratory for Nuclear Science 77 Massachusetts Ave. Cambridge, MA *(8 MeV unit put in storage in 1970, 4 MeV unit dismantled in 1960, 2 MeV unit transferred to Boston Museum of Science in 1950)	1-8 MeV V. de Graaff 1-4 MeV V. de Graaff 1-9 MeV V. de Graaff (1951) 1-2 MeV V. de Graaff 1-10 MeV V. de Graaff	5,22 5,22 22 22 48
Minnesota, University of Minneapolis, MN *(dismantled in 1966)	1-4 MeV V. de Graaff	5,22,48
Monsanto Chemical Co. Dayton, OH	1-2 MeV V. de Graaff	5
Montana State University Bozeman, MT	1-3.5 MeV V. de Graaff (1971)	22
Murray State University Bowling Green, KY	1-6 MeV V. de Graaff	12

Facility and Location	Number and Type (First Beam)	Reference
NASA-Space Radiation Effects Laboratory College of William and Mary Newport News, VA *(mothballed in 1979)	1-3 MeV Dynamitron (1966)	22
National Accelerator Laboratory 200/500 GeV Synchrotron Injector Weston, IL	1-0.75 MeV Cockroft-Walton	30
National Bureau of Standards Washington, DC	1-0.25 MeV Cockroft-Walton 1-2 MeV V. de Graaff (1955)	5 5,22
National Institutes of Health Public Health Service Bethesda, MD	2-2 MeV V. de Graaff 1-3 MeV V. de Graaff	5 5
Nebraska, University of Lincoln, NE	1-0.4 MeV Cockroft-Walton	5
Nevada, University of Reno, NV	2-5 MeV V. de Graaff (long time)	50
New Hampshire, University of Durham, NH (*unit has not been in use since 1979)	1-400 kV V. de Graaff (1960)	53
Northwestern University Evanston, IL *(stored in 1968)	1-5 MeV V. de Graaff	5,22
Notre Dame University Notre Dame, IN	1-4 MeV V. de Graaff (1956) 1-2 MeV V. de Graaff	5,22,53 22
Oak Ridge National Laboratory Oak Ridge, TN	1-3 MeV V. de Graaff (1948) 1-0.25 MeV Cockroft-Walton 1-6 MeV V. de Graaff (1950)	5,22 5 5,22
Ohio State University 1314 Kinnear Road Columbus, OH *(2 MeV unit dismantled in 1962)	1-2 MeV V. de Graaff 1-6 MeV V. de Graaff (1963)	22 22,43,48
Oregon Health Sciences University (Formerly University of Oregon Health Science Center) 3181 S.W. Sam Jackson Road Portland, OR 97201	1-4.5 MeV V. de Graaff (1966)	16,22
Oregon, University of Eugene, OR	1-4 MeV Van de Graaff	22,48

Facility and Location	Number and Type (First Beam)	Reference
Pennsylvania, University of Philadelphia, PA	1-3 MeV V. de Graaff	5
Penn State University University Park, PA *(shutdown in 1973)	1-5.5 MeV V. de Graaff (1963)	13,22
Pittsburgh, University of Pittsburgh, PA	3-V. de Graaff	13
Pondville State Hospital Wrentham, MA	1-2 MeV V. de Graaff	5
Princeton University Princeton, NJ	1-3 MeV V. de Graaff	5
Radio Corporation of America Princeton, NJ	1-1 MeV V. de Graaff	5
Redstone Arsenal Huntsville, AL	1-2 MeV V. de Graaff	5
Rensselaer Polytechnic Institute Troy, NY	1-0.25 MeV Cockroft-Walton 1-1 MeV V. de Graaff	5 5
Reynolds Metals Co. Bauxite, AR *(Moved to U. of Arkansas, Fayetteville, in 1975)	1-Cockroft-Walton	6
Rice University 6100 S. Main Houston, TX	1-0.2 MeV Cockroft-Walton 1-6 MeV V. de Graaff (1953)	5 5,22,44, 48
Sandia Corp. Albuquerque, NM	1-2 MeV V. de Graaff	5
Shell Development Co. Houston, TX	1-2 MeV V. de Graaff	5
Shell Development Co. Emeryville, CA	1-3 MeV V. de Graaff	5
Socony-Vacuum Oil Co. Paulsboro, NJ	1-2 MeV V. de Graaff	5
South Carolina, University of Columbia, SC	1-0.5 MeV V. de Graaff (1962)	22,34
State University of New York at Albany Albany, NY	1-4 MeV Dynamitron (1970)	22

Facility and Location	Number and Type (First Beam)	Reference
Swedish Hospital Seattle, WA	1-2 MeV V. de Graaff	5
Stanford Research Institute Palo Alto, CA	1-3 MeV V. de Graaff (1960)	5,22
Tennessee, University of at Chattanooga Dept. of Physics Chattanooga, TN *(currently not in use)	1-Cockroft-Walton	32
Texas Engineering Experiment Station College Station, TX	1-Cockroft-Walton	48
Texas Oil Co. New York, NY	1-3 MeV V. de Graaff	5
Texas, University of Austin, TX *(2 MeV unit dismantled in 1962)	1-4 MeV V. de Graaff (1963) 1-2 MeV V. de Graaff	5,22 22
Tulane University New Orleans, LA *(sold in 1973)	1-3.0 MeV V. de Graaff (1967)	22
University Hospitals Cleveland, OH	1-2 MeV V. de Graaff	5
Upjohn Co. Kalamazoo, MI	1-2 MeV V. de Graaff	5
Union Carbide and Carbon Corp. Bakelite Division Bloomfield, NJ	1-2 MeV V. de Graaff	5
U.S. Air Force, Air Material Command Wright-Patterson Air Force Base Dayton, OH	1-2 MeV V. de Graaff	5
U.S. Army Chemical Center Chemical & Radiological Laboratory Army Chemical Center, MD	1-0.3 MeV V. de Graaff	5
U.S. Army Quartermaster Corps Natick, MA	1-1 MeV V. de Graaff	5
U.S. Naval Hospital Bethesda, MD	1-2 MeV V. de Graaff	5

Facility and Location	Number and Type (First Beam)	Reference
U.S. Naval Postgraduate School Monterey, CA	1-2 MeV V. de Graaff	5
U.S. Naval Radiological Defense Laboratory San Francisco, CA	1-2 MeV V. de Graaff	5
U.S. Naval Research Laboratory Washington, DC *(one 2.0 MeV V. d Graaff was dismantled in 1966)	1-0.5 MeV Cockroft-Walton	5
	1-0.25 MeV Cockroft-Walton	5
	1-2.1 MeV V. de Graaff	5
	2-2.0 MeV V. de Graaff	5,22
	1-6.0 MeV V. de Graaff (1953)	5,22
Upjohn Company 301 Henrietta Kalamazoo, MI	1-2 MeV V. de Graaff (1950)	39
Utah, University of Salt Lake City, UT	1-2 MeV V. de Graaff	29
Virginia Polytechnic Institute Blacksburg, VA	1-4 MeV V. de Graaff (1968)	22
Virginia, University of Charlottesville, VA	1-6 MeV V. de Graaff (1966)	5,22,48
Washington State University Pullman, WA *(shutdown in 1973)	1-2 MeV V. de Graaff (1965)	22
Watertown Arsenal Watertown, MA	1-2 MeV V. de Graaff	5
Wayne State University 645 Mullett St. Detroit, MI	1-5 MeV V. de Graaff (1970)	37
Wells Surveys, Inc. Tulsa, OK	1-0.65 MeV V. de Graaff	5
West Virginia University Morgantown, WV	1-2 MeV V. de Graaff (1964)	22
Westinghouse Tampa, FL	1-2.5 MeV V. de Graaff	10
	2-4 MeV V. de Graaff	10
Westinghouse Electric Corp. Commercial Atomic Power Pittsburgh, PA	3-2 MeV V. de Graaff	5
	1-6 MeV V. de Graaff	
Westinghouse Electric Churchill, PA	1-V. de Graaff	13

Facility and Location	Number and Type (First Beam)	Reference
Westinghouse Electric Bettis Atomic Power Laboratory West Mifflin, PA	3-V. de Graaff	13
Wilmington Medical Center Dept. of Radiation Therapy Wilmington, DE 19899	2-V. de Graaff	58
Wisconsin, University of Madison, WS	1-2 MeV V. de Graaff	5
	1-4.5 MeV V. de Graaff	5
	1-0.2 MeV Activitron	55
	1-0.15 MeV Cockroft-Walton	55
Worcester Polytechnic Institute Worcester, MA	1-2 MeV V. de Graaff (1959)	22

Neutron Generators

Facility and Location	First Beam	Reference
Argonne National Laboratory Fast Neutron Generator 9700 S. Cass Avenue Argonne, IL	1970	4
Brown University Nuclear Laboratory 300 KeV Neutron Generator 75 Butler Ave. Providence, RI		20
Brown University Prince Engineering Laboratory 300 KeV Neutron Generator 355 Brook St. Providence, RI		20
Consolidated Rail Corporation 14 MeV neutron generator 577 East 152nd St. Cleveland, OH		43
Dresser Atlas Division of Dresser Industries, Inc. Neutron Generator 10201 Westheimer Houston, TX 77001		6
Drexel Institute of Technology Neutron Generator Philadelphia, PA		13
Gulf Research and Development Neutron Generator Pittsburgh, PA		13
Kansas State University 14 MeV Neutron Generator Manhattan, KS *(closed out in 1975)		17
Kansas University Neutron Generator Lawrence, KS		40
Memphis State University Neutron Generator Dept. of Physics Memphis, TN		32

Facility and Location	First Beam	Reference
Pennsylvania State University Neutron Generator University Park, PA		13
St. Mary's University Neutron Generator 2700 Cincinnati Ave. San Antonio, TX		44
Tennessee, University of Dept. of Nuclear Engineering Sealed Neutron Generator Daugherty Engineering Building Knoxville, TN *(currently not in use)		32
Texas Christian University Neutron Generator Ft. Worth, TX		44
Texas, University of, at Austin Neutron Generator 2617 Speedway, #104 Austin, TX		44
Texas A&M University Neutron Generators College Station, TX		44
Texas Tech University Neutron Generator Lubbock, TX		44
Universal Woods 200 keV Neutron Generator 2600 Grassland Drive Louisville, KY		12
U.S. Steel Corporation 2-Neutron Generators Monroeville, PA		13
Westinghouse Electric Neutron Generator Churchill, PA		13
Westinghouse Electric Bettis Atomic Power Laboratory Neutron Generator West Mifflin, PA		13
Wilkes College Neutron Generator Wilkes-Barre, PA		13

Facility and Location	First Beam	Reference
Wisconsin, University of 2-Neutron Generators Madison, WI		55
Wyoming, University of 14 MeV Neutron Generator Casper, WY		48

Tandem Accelerators

Facility and Location	First Beam	Reference
Aerospace Research Laboratory 8 MeV tandem Van de Graaff (no address)	1967	22
Argonne National Laboratory 18 MeV Tandem Van de Graaff Argonne, IL	1967	4,22
Argonne National Laboratory Tandem Dynamitron Argonne, IL		22
Bell Telephone Murray Hill, NJ		48
Brookhaven National Laboratory 30 MeV Tandem Van de Graaff Building 901A Upton, NY	1970	4,22
California Institute of Technology Kellogg Radiation Laboratory 10 MeV Tandem Accelerator Pasadena, CA	1961	4,22
Florida State University 10 MeV Tandem Van de Graaff Laboratory Dept. of Physics Tallahassee, FL	1971	4,5,10
High Voltage Engineering Corp. Burlington, MA	1969	4
Kansas State University 12 MeV Tandem Van De Graaff Manhattan, KS	1969	4,17,22
Kansas State University Los Alamos Tandem Van de Graaff Manhattan, KS *(closed out in 1970's)		17
Lawrence Livermore Laboratory 27 MeV Cyclograaff Laboratory L-330 Livermore, CA *(Transferred from Florida State University)	1971	4,22

Facility and Location	First Beam	Reference
Los Alamos Scientific Laboratory 3-Stage 24.5 MeV Tandem Accelerator Facility Los Alamos, NM	1964	4,22
Minnesota, University of Williams Laboratory of Nuclear Physics 20 MeV Tandem van de Graaff Facility Minneapolis, MN	1966	4,22
Notre Dame University Nuclear Structure Laboratory 15 MeV Tandem van de Graaff Facility Department of Physics Notre Dame, IN	1968	4,22,48,52
Oak Ridge National Laboratory 13 MeV Tandem van de Graaff Laboratory Building 5500 Oak Ridge, TN	1962	4,22
Ohio University John E. Edwards Accelerator Laboratory 11 MeV Tandem van de Graaff Facility Athens, OH	1970	4,22
Pennsylvania, University of 12 MeV Tandem Accelerator Laboratory Department of Physics 209 S. 33 Street El Philadelphia, PA *(dismantled and transferred to Sandia Labs in 1974)	1962	4,22
Pittsburgh, University of Scaife Nuclear Physics Laboratory 18 MeV 3-stage Tandem Van de Graaff Pittsburgh, PA	1967	4,22
Purdue University Purdue Accelerator Laboratory 15 MeV Tandem Van de Graaff Lafayette, IN	1969	4,22,48
Rice University T. W. Bonner Nuclear Labs. 12 MeV Tandem Van de Graaff Houston, TX	1961	4,22,48
Rochester, University of Nuclear Structure Research Laboratory 20 MeV Tandem Van de Graaff River Campus Station Rochester, NY	1966	4,22

Facility and Location	First Beam	Reference
Rutgers University Nuclear Physics Laboratory 18 MeV Tandem Van de Graaff New Brunswick, NJ	1964	4,22
Stanford University 19 MeV Tandem Van de Graaff Laboratory Dept. of Physics Stanford, CA	1965	4,22
State University of New York at Stony Brook Nuclear Structure Laboratory 17 MeV Tandem van de Graaff Facility Stony Brook, NY	1968	4,22
Texas, University of Center for Nuclear Studies 17.5 MeV 3-stage Tandem Van de Graaff Austin, TX *(mothballed in 1977)	1963	4,22
Triangle University Nuclear Laboratory 15 MeV Tandem Van de Graaff Duke University Durham, NC	1968	4
U. S. Army Ballistic Research Laboratories Radiation Laboratory Aberdeen Proving Ground, MD *(Sent to U. of Pennsylvania in 1975)	1969	4
U.S. Army Nuclear Effects Laboratory Edgewood Arsenal 15 MeV Tandem Van de Graaff (no address)	1969	22
Washington, University of Nuclear Physics Laboratory 25.5 MeV 3-stage Tandem Van de Graaff Seattle, WA	1967	4,22
Western Michigan University Accelerator Laboratory 12 MeV Tandem Van de Graaff Physics Dept. Kalamazoo, MI	1969	4,22,48
Wisconsin-Madison, University of 12 MeV Tandem Van de Graaff Sterling Hall Madison, WI	1960	4,5,22,52

Facility and Location	First Beam	Reference
Yale University Arthur William Wright Nuclear Structure Laboratory 22 MeV Tandem Van de Graaff New Haven, CT	1966	4,22

Ion Implanters[*]

Facility and Location	Number of Units	Reference
Hewlett-Packard 100 N.E. Circle Blvd. Corvallis, OR 97330	5	16
Intel Corporation 3585 S.W. 198th Avenue Aloha, OR 97005	12	16
Tektronix, Inc. Beaverton, OR 97005	5	16
Georgia Institute of Technology Dept. of Physics 225 North Avenue Atlanta, GA	1	31

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[*] These units are used by the semi-conductor industry to implant ions in silicon and germanium. (Ce 79)

Cohesive Binders*

Facility and Location	Number and Energy of Units	Reference
Barnwell Mills Barnwell, SC	1-0.5 MeV	34
Magnolia Finishing Plant Blacksburg, SC *(inoperative)	1-0.5 MeV	34
Milliken Research Spartanburg,SC	1-0.5 MeV	34
Pirelli Cable Corporation 28 Bypass Abbeville, SC	3-0.75 MeV	34
Polymer Industries Greenville, SC	1-0.175 MeV	34
United Merchants & Manufacturers Inc. Langley, SC	1-0.175 MeV	34
Name Withheld Address Withheld	23-0.5 MeV units at two locations	34

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*These units are used in the state of SC for irradiating fabric and cable to increase its resistance to tearing.

Storage Rings

Facility and Location	First Beam	Reference
Stanford University SPEAR 2.5 GeV Electron Storage Ring Stanford Linear Accelerator Center Stanford, CA	1972	1,22
Wisconsin, University of Tantalus I 240 MeV Storage Ring Madison, WI	1968	22

APPENDIX B.
PERTINENT LITERATURE

APPENDIX B.
Bibliography

Al46 Alvarez, L.W., 1946, "The Design of a Proton Linear Accelerator," Physical Review 70, 799.

Ar79 Arrowsmith, H.W., July-September 1979, "Decontamination and Decommissioning of Hanford Facilities - Technologies," Nuclear Waste Management Quarterly Progress Report, Pacific Northwest Laboratory, PNL-3000-3.

Aw69 Awschalom, M., F.L. Larsen, W. Schimmerling, 1969, "Activation of Air Near a Target Bombarded by 3 GeV Protons," Nuclear Instruments and Methods 75, 93-102.

Ba69 Barbier, Marcel, 1969. Induced Radioactivity, (Amsterdam-London: North Holland Publishing Company).

Be58 Behman, Gerald A., 1958, "Particle Accelerators," University of California, Radiation Laboratory, Berkeley, CA, January 1, 1958.

Bo61 Boom, R.W., K.S. Toth, A. Zucker, 1961, "Residual Radiation of the LRL 184-Inch Cyclotron," Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-3158.

Bu69 Burrill, E.A., 1969, "The Expanding Use of Particle Accelerators in Research, Medicine and Industry: A Statistical Review," in Proceedings of the Second International Conference on Accelerator Dosimetry and Experience, Stanford, CA, November 5-7, 1969, CONF-691101.

Ce79 Cehn, Joel, August 1979, "A Study of Radioactive Airborne Effluents from Particle Accelerators," Prepared for U.S. Environmental Protection Agency by Teknekron Research, Inc., McLean, VA. ORP/TAD 79-12.

Ch79 Choquet, R. and F. Clapier, 1979, "Data on the Activation and Dismantling of the 155 MeV Synchrocyclotron of the Institute of Nuclear Physics at Orsay," Radioprotection, 14(2), p. 81.

Co76 Cohen, S.C., et al., December 1976, "Evaluation of Occupational Hazards from Industrial Radiation: A Survey of Selected States," U.S. Department of Health, Education and Welfare, Publication No. (NIOSH) 77-142.

Co80 Conti, E.F., March 1980, "Residual Activity Criteria for Decommissioning." Proceedings of a Nuclear Energy Agency Specialist Meeting, U.S. Nuclear Regulatory Commission, Paris, France, March 17-19, 1980, CONF-800359.

Fu70 Fulmer, C.B. and G. Kindred, 1970, "Calculated Residual Radiation Levels for Some Elements Used in Cyclotron Structures," Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-TM-2834.

Ga70 Gabriel, T.A., 1970, "Calculation of Long-Lived Activity in the Soil Around High-Energy Accelerator Target Areas," Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-TM-3033.

Gi64a Gilbert, W.S., 1964, "Induced Activity and Radiation Damage," Lawrence Radiation Laboratory internal report, UCID-10014.

Gi64b Gilbert, W.S., 1964, "Shutdown Gamma Radiation Fields in an AGS Tunnel: Causes and Cures," Lawrence Radiation Laboratory internal report, UCID-10137.

Gi65 Gilbert, W.S. and R.H. Thomas, 1965, "Problems of Induced Radioactivity Around the 200 BeV AGS," in Proceedings of the 1st International Particle Accelerator Conference, Washington, D.C., March 10-12, 1965.

Go76 Gollon, P.J., August 1976, "Production of Radioactivity by Particle Accelerators," in IEEE Transactions in Nuclear Science, NS-23(4).

Gr81 Personal communication, Dr. Graham Grundy, American College of Radiology, Patterns of Care Study, November, 1981.

Ho67 Howard, F.T., October 1967, "High Energy Accelerators - 1967," Accelerator Information Center, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-AIC-1.

Ho69 Howard, F.T., September 1969, "Isochronous Cyclotrons - 1969,"Prepared by Accelerator Information Center, Oak Ridge National Laboratory, Oak Ridge TN for The International Cyclotron Conference, Oxford, England, September 17-19, 1969.

Ho74 Howard, F.T., December 1974, "Tandem Accelerators - 1973-74," Accelerator Information Center, Oak Ridge National Laboratory, Oak Ridge, TN, ORNL-TM-4934.

IAEA76 International Atomic Energy Agency, 1976, "Decommissioning of Nuclear Facilities," Report of a Technical Committee Meeting. Organized by the IAEA, Vienna, Austria, October 20-24, 1975. IAEA-179.

ICRP59 International Commission on Radiological Protection (ICRP), 1959, Report of Committee 2 on Permissible Dose for Internal Radiation, Publication 2, (New York: Pergamon Press).

ICRP77 International Commission on Radiological Protection (ICRP), 1977, Annals of the ICRP Publication 26, (New York: Pergamon Press).

ICRU78 International Commission on Radiation Units and Measurements (ICRU), 1978, "Basic Aspects of High Energy Particle Interactions and Radiation Dosimetry," ICRU Report No. 28.

Ka64 Karetnikov, D.V., I.N. Slivkov, V.A. Teplyakov, A.P. Fedotov, B.K. Shembel, March 1964, "Linear Ion Accelerators," USAEC, Division of Technical Information, AEC-tr-6229.

Ke41 D.W. Kerst, "The Acceleration of Electrons by Magnetic Induction," in Physical Review, 60, 47 (1941).

Lan78 Lane, R. G., B. R. Paliwal, D. D. Tolbert, 1978, "Leakage Radiation Characteristics of an 18 MeV Clinical Linear Accelerator" in Health Physics, 35, p. 485.

Lap72 Lapp, R.E. and H.L. Andrews, 1972, Nuclear Radiation Physics, 4th Edition, (Englewood Cliffs, NJ: Prentice-Hall, Inc.).

Lo64 Loysen, P., June 1964, "Economics of Building Decontamination," Surface Contamination, Proceedings of a Symposium in Gatlinburg, TN, U.S. Atomic Energy Commission, (New York: Pergamon Press).

Ma78 Martin, John A., 1978, "Cyclotrons - 1978," Holifield Heavy Ion Research Facility, Oak Ridge National Laboratory, for The 8th International Conference on Cyclotrons and their Applications, Indiana University, Bloomington, IN, September 18-21, 1978.

Mu78 Mundis, R.L., M.J. Kikta, G.J. Marmer, J.H. Opelka, J.M. Peterson, B. Siskind, 1978, "Health Physics Considerations in Accelerator Decommissioning and Disposal," Argonne National Laboratory.

Mu81 Murphy, E.S., 1981, "Technology, Safety and Costs of Decommissioning Reference Non-Fuel Cycle Nuclear Facilities," Pacific Northwest Laboratory, Richland, WA. NUREG/CR-1754.

NAS68 National Academy of Sciences, 1968, "New Uses for Low-Energy Accelerators," Prepared by the ad hoc Panel on New Uses for Low Energy Accelerators of the Committee on Nuclear Science. National Research Council, Washington, D.C.

NBS70 National Bureau of Standards, June 1970, "Radiological Safety in the Design and Operation of Particle Accelerators," ANSI Subcommittee N43-4, NBS Handbook 107.

NCRP77 National Council on Radiation Protection and Measurements, 1977, "Radiation Protection Design Guidelines for 0.1-100 MeV Particle Accelerator Facilities," Scientific Committee 22 on Radiation Shielding for Particle Accelerators, NCRP Report No. 51.

Nea68 Neal, R.B., et al., 1968, The Stanford Two-Mile Accelerator, (New York: W.A. Benjamin, Inc.).

Nel69 Nellis, D.O., E.L. Hudspeth, I.L. Morgan, P.S. Buchanan, R.F. Boggs, 1969, "Tritium Contamination in Particle Accelerator Operation," U.S. Department of H.E.W., Public Health Service.

Op79a Opelka, J.H., M.J. Kikta, G.J. Marmer, R.L. Mundis, J.M. Peterson, B. Siskind, 1979, "A Decommissioning Plan for Particle Accelerators," Prepared for Decontamination and Decommissioning of Nuclear Facilities, American Nuclear Society, Sun Valley, ID, September 16-19, 1979. Argonne National Laboratory.

Op79b Opelka, J.H., G.J. Marmer, R.L. Mundis, J.M. Peterson, B. Siskind, June 1979, "Reutilization Potential of Accelerator Components: A Decommissioning Perspective," IEEE Transactions on Nuclear Science, NS-26 (3).

Op79c Opelka, J.H., R.L. Mundis, G.J. Marmer, J.M. Peterson, B. Siskind, M.J. Kikta, December 1979. "Particle-Accelerator Decommissioning," Argonne National Laboratory, ANL/ES-82.

Pa73 Patterson, H.W., and R.H. Thomas, 1973, Accelerator Health Physics, (London, England: Academic Press).

Per76 Pernet, A., (ed) 1976, Nuclear Research Index, (British Isles: Francis Hodgson Books, Ltd).

Pet79 Peterson, J.M, J.H. Opelka, R.L. Mundis, 1979, "Waste Management Considerations in Particle Accelerator Decommissioning," in Transactions of the American Nuclear Society 25th Annual Meeting, Volume 32, TANSAO 32 1-832.

Pr76 Price, K.W. and G.R. Holeman, 1976, "Health Physics Aspects of the Yale Heavy Ion Linear Accelerator Dismantling Project" in Proceedings of the Ninth Midyear Topical Symposim of the Health Physics Society, Denver, CO, February 9-12, 1976.

Ra64 Ratner, B.S., 1964. "Accelerators of Charged Particles," translated by L.A. Fenn, translation edited by H.W. Curtis, (New York: Pergamon Press).

RAC78 Resources Agency of California, 1978. "Radioactive Materials in California," Sacramento, CA, NP-23549.

Re81 Personal Communication with Henry Rechen, Deputy Director, Division of Electronic Products, Bureau of Radiological Health, December 1981.

Sh81 Personal communication, Heyward Shealy, South Carolina Department of Health and Environmental Control, Bureau of Radiological Health, November, 1981.

Su65 Sullivan, A.H. and T.R. Overton, 1965. "Time Variation of the Dose Rate for Radioactivity Induced in High Energy Accelerators," Health Physics, 11, 1101.

Sw79 Swanson, W.P., "Radiological Safety Aspects of the Operation of Electron Linear Accelerators."

Th Thomas, R.H., "Possible Contamination of Ground Water Systems by High Energy Proton Accelerators," Lawrence Radiation Laboratory, University of California, Berkeley, CA.

USBRH75 U.S. Bureau of Radiological Health, 1975, The Use of Electron Linear Accelerators in Medical Radiation Therapy, Overview Report No. 2. Market and Use Characteristics: Current Status and Future Terms.

USBRH77 U.S. Bureau of Radiological Health, 1977, Report of the State and Local Radiological Health Programs Fiscal Year 1977, HEW Publication No. 78-8034.

USGAO77 United States General Accounting Office, June 1977. "Cleaning Up the Remains of Nuclear Facilities - A Multibillion Dollar Problem." EMD-77-46.

USNRC74 United States Nuclear Regulatory Commission, June 1974. "Termination of Licenses for Nuclear Reactors," Regulatory Guide 1.86.

Va31 Van de Graaff, R.J., 1931. "A 1,500,000-Volt Electrostatic Generator," in Physical Review 48, 315.

Va68 Vasil'ev, A.A., (ed), October 1968, "1000 GeV Cybernatic Proton Accelerator," USAEC, Division of Technical Information, AEC-tr-6949.

Wa69 Warren, G.J., D.D. Busick and R.C. McCall, 1969, "Radioactivity Produced and Released from Water at High Energies" in Proceedings of the Second International Conference on Accelerator Dosimetry and Experience, CONF-691101, Stanford, CA, November 5-7, 1969.

We80 Welsh, R.E. A Determination of the Level of Activation Products in the SREL Wall, College of William and Mary, Williamsburg, VA.

Wo75 Wolf, A.P. October 1975, "Medical Cyclotrons," Brookhaven National Laboratory, BNL-22021.

"Catalogue of High Energy Accelerators" in Proceedings of the IXth International Conference on High Energy Accelerators, Stanford University, May 2-7, 1974.

Decontamination and Decommissioning of Nuclear Facilities Conference, September 16, 1979. Summary Report, Sun Valley, ID.

"Life-Time of Tritium Targets and Release of Tritium from D-T Neutron Generators," 1971, in the International Journal of Applied Radiation and Isotopes, Volume 22, Pergamon Press, pp. 486-489.